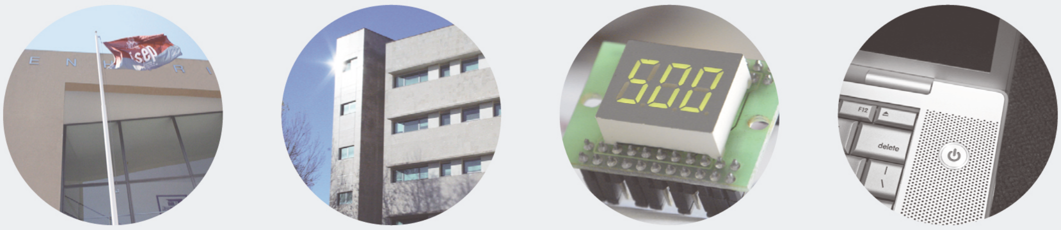
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MESTRADO EM ENGENHARIA ELECTROTÉCNICA - SISTEMAS ELÉCTRICOS DE ENERGIA



# Battery Energy Storage System Optimal Sizing in a Battery Electric Vehicle Fast Charging Infrastructure

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POLITÉCNICO
DO PORTO

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“The first problem for all of us, men and women, is not to learn but to unlearn.”

Gloria Steinem

# *Acknowledgements*

I take the opportunity of this section to acknowledge; my parents, my brother and my nephew for all the support and motivation along these years; my girlfriend Natália for all the love and companionship; and last but not least to my professors and Ismael who guided and mentored me in this dissertation.

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# *Abstract*

The growing number of battery electric vehicles and plug-in hybrid electric vehicles brings the need of more fast charging stations across cities and highway stops. This charging stations toned to be connected to the electrical grid via existent facilities, causing constraints such as power availability.

This work brings an approach for the planning and operation of such energy hubs by coping with this challenge by deploying a Battery-based Energy Storage System (BESS). With the BESS integration, it is expected to minimize utilization and overall energy costs, preventing infrastructure upgrades, and enhancing the integration of renewable energy resources.

This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages, integrated into an electrical installation that will implement fast charging stations. This sizing is a result of an optimization based on the interior point algorithm, where the objective is to minimize the costs of maintenance, operation, and installation of a BESS, while properly modelling the different resources such as the BESS, the charging station and Electric Vehicles (EV) charging and Photovoltaic generation (PV).

In order to have an estimate of necessary power and energy consumption, a simulated frequency of parking of BEVs at the charging stations, based on probabilities, was modelled taking into account the distance that a battery electric vehicle will do in a certain period of time and the probability of being a car with a particular set of characteristics.

***Keywords***

Battery Energy Storage System; Fast Charging Stations; Battery Electric Vehicle

# *Resumo*

O número de crescente de veículos elétricos (VE) e híbridos *plug-in* dá azo à necessidade de mais infraestruturas de carregamento, deste tipo de veículos, nas cidades e nas paragens nas autoestradas. Estas infraestruturas têm de estar ligadas à rede elétrica de distribuição, causando restrições como disponibilidade de potência.

Este trabalho centra-se numa abordagem para o planeamento e operação destas *hubs* energéticas ao implementar Sistemas de Armazenamento de Energia em Baterias (SAEB). Com a integração de SAEB é expectável a minimização dos custos globais de energia e evitar atualizações na infraestrutura, e potencializar a integração de Recursos de Energia Renovável (RER).

O âmbito deste trabalho é dimensionar um sistema de armazenamento de energia estacionário com baterias de ião-lítio através de uma co otimização do planeamento e operação, integrado numa instalação elétrica na qual estão implementados carregadores rápidos de veículos elétricos. O dimensionamento resulta de uma otimização baseado no algoritmo do ponto interior, onde o objetivo é minimizar os custos de manutenção, operação e instalação dos SAEB, enquanto são modelizados recursos como o SAEB, a infraestrutura de carregamento e o carregamento dos VE e produção fotovoltaica.

De modo a estimar a potência necessária e a energia consumida, simulou-se a frequência de carregamento dos VE na infraestrutura de carregamento, baseado em probabilidades, modelizado tendo em conta a distância que a bateria do veículo elétrico consegue durar num determinado período de tempo e a probabilidade de esse veículo ter certas características.

### **Palavras Chave**

Sistema de Armazenamento de Energia em Baterias, Infraestruturas de carregamento rápido; Veículo Elétrico

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# *Acronyms*

AC – Alternating Current

BESS – Battery Energy Storage System

BMS – Battery Management System

CAES – Compressed Air Energy Storage

CEME – Electricity Provider for Electric Mobility

CSP – Concentrated Solar Power

DC – Direct Current

DG – Distributed Generation

DGEG – General Directorate of Energy and Geology

DL – Decree Law

DoD – Depth of Discharge

DSO – Distribution System Operator

EGME – Managing Entity of the Electric Mobility Network

EMR – Electric Mobility Regulation

ERSE – Energy Services Regulatory Entity

EU – European Union

EV – Electric Vehicles

FESS – Flywheel Energy Storage System

IEC – International Electrotechnical Committee

IGBT – Insulated Gate Bipolar Transistor

LV – Low Voltage

MV – Medium Voltage

OPC – Charging Point Operator

PHS – Pumped Hydroelectric Storage

PNEC – National Integrated Energy and Climate Plan

PUG – Public Utility Grid

REC – Renewable Energy Communities

RES – Renewable Energy Sources

SET Plan – European Strategic Energy Technology Plan

SMES – Superconducting Magnetic coil Energy Systems

SoC – State of Charge

SoH – State of Health

SPU – Self-consumption Production Units

UVE – User of Electric Vehicles

# 1. INTRODUCTION

## 1.1. MOTIVATION

The efforts made to decrease the greenhouse emissions, through the world, are increasing and the reduction of the consumption of fossil fuels is one of the main focus of the environmental policy. One of the biggest consumers of fossil fuels is transportation, which leads the governments are giving incentives to buy vehicles that are powered by electric energy. This diminishes the usage of petroleum derivatives because people opt to buy electric vehicles.

The growing number of battery electric vehicles and plug-in hybrid electric vehicles entails the need of fast charging stations across cities and highway stops. This charging stations toned to be connected to the electrical grid via existent facilities, causing constraints such as:

- power availability;
- power losses;
- power quality;
- grid reliability.

To address the problems stated, applications of energy storage systems in the charging infrastructures are being studied as a very feasible option. The integration of such systems can provide lower costs of operation of the fast charging station.

## 1.2. DISSERTATION SCOPE AND OBJECTIVES

The scope of this dissertation brings an approach for the planning and operation of such energy hubs by coping with this challenge by deploying a Battery-based Energy Storage System (BESS). With the BESS integration, it is expected to minimize utilization and overall energy costs, preventing infrastructure upgrades, and enhancing the integration of renewable energy resources.

This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages, integrated into an electrical installation that will implement fast charging stations. This sizing is a result of an optimization based on the interior point algorithm, where the objective is to minimize the costs of maintenance, operation, and installation of a BESS, while properly modelling the different resources such as the BESS, the charging station and EV charging and PV generation.

## 1.3. PUBLICATIONS

It was submitted and accepted a paper, for oral presentation, for the 4th E-Mobility Power System Integration Symposium, in Germany, part of the RE Grid Integration Week.

## 1.4. STRUCTURE

The dissertation is structured in five main chapters, as follows:

- Chapter 1 presents the motivation and the objectives of this dissertation as well as publications that originated from this work.
- Chapter 2 presents the state of the art on subjects such as microgrids, energy storage and electric mobility. Also, it summarizes the legal framework for these subjects, in Portugal and in Europe;

- Chapter 3 describes the methodology of the optimization tool that integrates a BESS in a fast charging station;
- Chapter 4 compares multiple scenarios of the case study;
- Chapter 5 concludes the dissertation by highlight the conclusions withdrawn from the scenarios comparison.

# 2. STATE-OF-THE-ART

## 2.1. LEGAL FRAMEWORK

In the scope of this work, it is held an analysis of the legal framework in Portugal, about Electric Mobility, Self-Consumption and Energy Storage. In each of these topics, the European directives, that influenced the legislation, are also addressed.

### 2.1.1. SELF-CONSUMPTION

#### 2.1.1.1. LICENSE, COMMUNICATION AND INSPECTION

In the decree law 162/2019 [1], there is a set of rules that establish the obligation of information and requirements, in order to make it possible to install methods of production of electric energy in order to consume it or to sell it to the electrical grid to which the installation is connected.

These requirements may be of technical specification or information that is owed to *Entidade Reguladora dos Serviços Energéticos* (1) (ERSE) or to *Direção Geral de Energia e Geologia* (2) (DGEG).

Facilities are divided by installed power, each one of these has communications and/or licensing requirements. They are divided as follows:

- Peak power equal to or less than 350W; does not need registration or communication obligation to DGEG
- Peak power between 350W and 35kW; needs prior notification to DGEG
- Peak power between 35kW and 1MW; needs prior notification to DGEG and obtaining a certificate of exploitation that translates into civil liability insurance
- Peak power above 1MW; needs production and exploration license

In the case of collective self-consumption units (condominiums, group of companies in an industrial park, etc.) they are required to have a remote energy meter that allows real-time communication with the distribution system operator (DSO), consumption and production data. The equipment that measures the energy produced by self-consumption production units (SPU) must allow the collection of the respective load diagram. Individuals with more than 4kW are also required to have remote energy meters that respect the same characteristics mentioned above.

The collective self-consumption management entity is responsible for informing the DSO of withdrawals or adherences and what is the intended coefficient for the distribution of production in case there is no communication. In this case, the system operator allocates one, for each installation, based on average consumption, in periods of 15-minutes.

Inspections of installations whose peak power is equal to or greater than 20.7kW are mandatory. Since its periodicity is every 10 years for installations up to 1MW, above this value, the inspection period will be every 8 years

#### 2.1.1.2. GRID CONNECTION

Installations that produce electricity for the purpose of self-consumption must always have a connection to the distribution grid. Due to the mandatory connection to the grid, the power inverters of these installations must be parameterized according to regulation 2016/631 of the

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(1) Regulatory Entity for Energy Sevices

(2) General Directorate of Energy and Geology

European Commission - establishing a network code on requirements for grid connection of generators [2].

Collective self-consumption requires a remote energy meter at points of interconnection with the public utility grid (PUG) and at each independent unit unless there is a connection to a smart grid. It is also mandatory to count electric energy extracted or injected in storage units associated with SPU when these are connected to the PUG. For the purpose of calculating the self-consumption balance, it is considered the aggregation of the energy consumed by SPU, the surplus injected into the grid and the consumption imported from the PUG, in periods of 15min.

The fact that these production units are connected to the grid, the system operator can reduce the power or temporarily turn it off, without compensation. However, this is only possible if there are technical problems that disrupt the operational limits of the electrical grid or its quality of service indicators.

The use of networks other than the public utility grid to transmit electricity between SPU and the independent units are exempt from payment. If PUG is in fact used, there are tariffs for access to the networks at the voltage level at which they prevail.

#### 2.1.1.3. ELECTRIC ENERGY MARKET

The new legislation creates changes in the electricity markets. The panorama of this subject has changed a lot with the growth of distributed generation (DG) and hence the market mechanisms and their agents have changed. DG is mostly composed of electricity production from renewable energy sources (RES). These producers, typically, represent small installations, that is, with low installed power. Because of their individual representation in the market being very small when compared to other producers, there are aggregators, in the sense of having a greater representation in the energy market. These agents of the electricity market were given the name of renewable energy communities (REC).

The new legislation allows RECs to produce, sell, consume and store renewable energy, namely through renewable energy purchase contracts, also granting access to all suitable energy markets, both directly and through aggregation. These communities will be held

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responsible for any deviations they cause in the national electricity system and may delegate responsibilities to a market participant or their designated representative. DGEG assesses, every 3 years, the existing obstacles to the development of RECs, and their potential.

The sale price will be freely fixed between producers and traders who contract the purchase of energy. By the end of 2025, all old contracts are valid, and the facilities will be governed by the new law.

The DSO must have access to the load diagram and to the production of the production units. If it is not possible to access by remote energy metering due to a fact attributable to the self-consumer, the distribution system operator will suspend the application of the balance in each 15min period.

Electric energy markets are evolving in pair with the distribution grid and the next big step for both is electric vehicles charging. These dynamic loads will prove a challenge for both, and the prospects is that not only they will be acting as loads but might be able to serve as dynamic energy storage units. Electric mobility will have a major impact on the future development of these subjects.

### 2.1.2. ELECTRIC MOBILITY

#### 2.1.2.1. LEGAL FRAMEWORK CONTEXTUALIZATION

The increase in sales of vehicles powered by electric energy (EV) led to the need of increasing public charging points, which required the creation of legislation to regulate these infrastructures and the transactions involving the EV charging process. In this logic, the Decree-Law (DL) 90/2014 [3] was published in *Diário da República* (3), which replaced DL 39/2010 [4]. The change in legislation was necessary to be in line with the European Parliament's directive 2014/94 [5]. This directive approves rules regarding the creation of an infrastructure for alternative fuels, in order to minimize dependence on oil and to mitigate the environmental impact of transport.

#### 2.1.2.2. LEGAL FRAMEWORK OBJECTIVE

In the 2014 Decree-Law there are three major differences, in comparison to the 2010 DL, which are listed below:

- Establishment and operation of EV charging points takes place in a competitive market
- Publicly accessible charging points include:
    - Private charging points
    - Charging points in public car parks
    - Charging points using registration cards
- Charging points must use smart meters

The approval of the electric mobility regulation (EMR) [6] is the responsibility of the Energy Services Regulatory Entity (ERSE). The EMR applies to all agents in the electric mobility sector and guarantees:

- Rules among sector players
- Regulation model and way of defining income to be applied to the managing entity of the electric mobility network (EGME)
- Measurement, reading and availability of charging and consumption data
- Regulated rates
- Service quality
- Price supervision

#### 2.1.2.3. PROVISION OF INFORMATION AND DYNAMICS BETWEEN THE ENTITIES OF THE ELECTRIC MOBILITY NETWORK

The user of electric vehicles (UVE) to charge their vehicle, must establish a link with one or more electricity providers for electric mobility (CEME). CEME is an entity that is licensed to operate charging points and to sell electricity for electric mobility. The charging point operator (OPC) is an entity whose activity consists of installing, providing, operating, and maintaining infrastructures in the electric mobility network that allow the vehicles to be charged. EGME is responsible for the management and monitoring of the electric mobility network. In this logic, it guarantees energy flow, provides system information and provides financial supervision in order to certify the functioning of the network [6].

Figure 1 helps to understand the dynamics that these entities may have between them. UVE can establish a contract with more than one CEME, each seller can have one or more contracts with the OPC and vice versa. However, the latter two agents must inform EGME of the contracts in place. The CEME must communicate all information related to energy and financial flows, while OPC must ensure conditions to allow UVE access to the charging points.

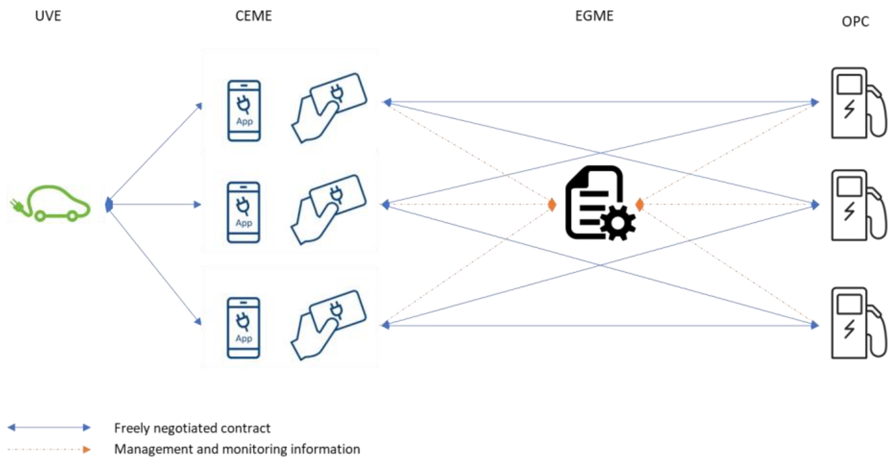

Figure 1 Diagram of relations between agents in the electric mobility sector

#### 2.1.2.4. INCOME AND RATES

EGME can never exceed the value defined by the equation in article 21 of [6]. This equation reflects the difference between the sum of capital costs and operating costs (accepted by ERSE) and the sum of subsidies and the recovery of the timeless deferral of income in the year t-n, with the adjustment finally being subtracted taking into account the values in recent years. However, EGME can propose tariffs and respective rules of application that result in lower profits than those established by ERSE.

In the EMR, rates differ between the rates that EGME applies to CEMEs, tariffs that it applies to OPCs and the tariff for access to electricity networks for electric mobility (ENEM).

The rates that EGME applies can never exceed the permitted income, according to article 21. Access fees to ENEMs are applied to sellers and EV users. These are defined by converting the prices of tariffs for access to the networks in medium voltage, special low voltage, and standardized low voltage for energy prices per hour, in euros per energy (€/kWh).

The tariff applicable to CEME and OPCs by EGME consists of a fixed tariff and one that depends on the number of charges. The calculation of these tariffs is defined in article 26 of [6].

The ENEM access tariff consists of active energy prices, broken down by hourly period, voltage level and type of supply.

### 2.1.3. ENERGY STORAGE SYSTEMS

Energy storage is a subject that has a non-defined position in regulation, either national or European. This is because energy storage system legislation is dependent on the application and on the agents of the place where the system will be located. There are systems that count as a load and/or as an energy source. In energy source field it could be considered as a distributed generator and a renewable energy source if attached to RES.

However, there are mentions of these systems in regulations and directives. This section will focus on the analysis of these documents, always with a focus on the scope of this work. A more technical approach will be done in section 2.1.3 of this work.

#### 2.1.3.1. CLIMATE ACTION

The European Union publishes several regulations and directives to promote, among member states, actions in the scope of sustainability. This promotion is reflected in regulations and directives.

In the case of climate action, the EU published the 2018/1999 [7] regulation. In article 22, it says that member states must include in national reports on energy security, the objectives for increasing the flexibility of the national energy system, through the deployment of domestic energy sources, demand response and energy storage. Article 23 refers to objectives such as increasing system flexibility, integration and association of markets, with the aim to increase the marketable capacity of existing interconnections, smart grids, aggregation, demand response, storage, distributed production, the mechanisms of dispatch, re-dispatching and de-triggering and price signals in real time.

#### 2.1.3.2. RENEWABLE ENERGY SOURCES PROMOTION

EU promotes the use of energy from renewable sources in the 2018/2001 [8] directive. This directive mentions the need to support the integration of energy from renewable sources in the transmission and distribution system as well as the use of energy storage systems for the integrated variable production of energy from RES. It promotes the development of decentralized generation technologies and the storage of renewable energy. The transition to decentralized energy generation has many advantages, such as using local energy sources, strengthening the security of energy supply at the local level, shortening transport distances, and reducing losses in energy transmission. Also, in this directive, the establishment of simplified and less costly authorization procedures, namely a simple notification procedure, for decentralized renewable energy generation and its storage, are mandatory.

#### 2.1.3.3. *PLANO NACIONAL INTEGRADO ENERGIA E CLIMA* 2021-2030

Analysing the *Plano Nacional integrado Energia e Clima 2021 – 2030* (4) (PNEC) [9], for the next decade, there is a strategy focused on the flexibility and stability of the national electricity system. The strategic objective of promoting the decarbonization of the industry, is in line with the discussed in the previous sections, which involves promoting the use of renewable resources, energy storage and electrification.

Energy storage is seen as a tool in this strategy, and there are no rules for establishing safety reserves. By 2030, PNEC foresees an increase in storage capacity; in an initial phase based on reversible pumped hydroelectric and in a more advanced phase of the decade in an initial contribution of battery and hydrogen technology.

PNEC considers energy storage to be adequate in the national energy system in scenarios of high penetration of renewable and intermittent energies in the energy mix. The integration of these systems can be centralized or decentralized, in front or behind the meter, with a focus on the flexibility and security of the energy system.

In the framework of research and innovation, the implementation of international groups under the European Strategic Energy Technology Plan (SET Plan) in areas of low carbon technology applying clean technologies and at lower costs. Included in these technologies are ocean energy, geothermal, solar with a focus on concentrated solar power (CSP), energy efficiency in industry and buildings, energy systems, intelligent communities, etc. This vision is aligned with the Portuguese strategy, namely in the areas of energy efficiency, clearly assuming the promotion of interinstitutional cooperation and the establishment of networks, namely in the fields of technologies that use renewable energy sources, energy storage, etc.

## 2.2. MICROGRIDS

### 2.2.1. CONCEPT

Microgrid is defined by [10] and [11], as a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. It has the ability to connect and disconnect from the main grid to enable it to operate in both grid-connected or island-mode, as clearly seen in Figure 2.

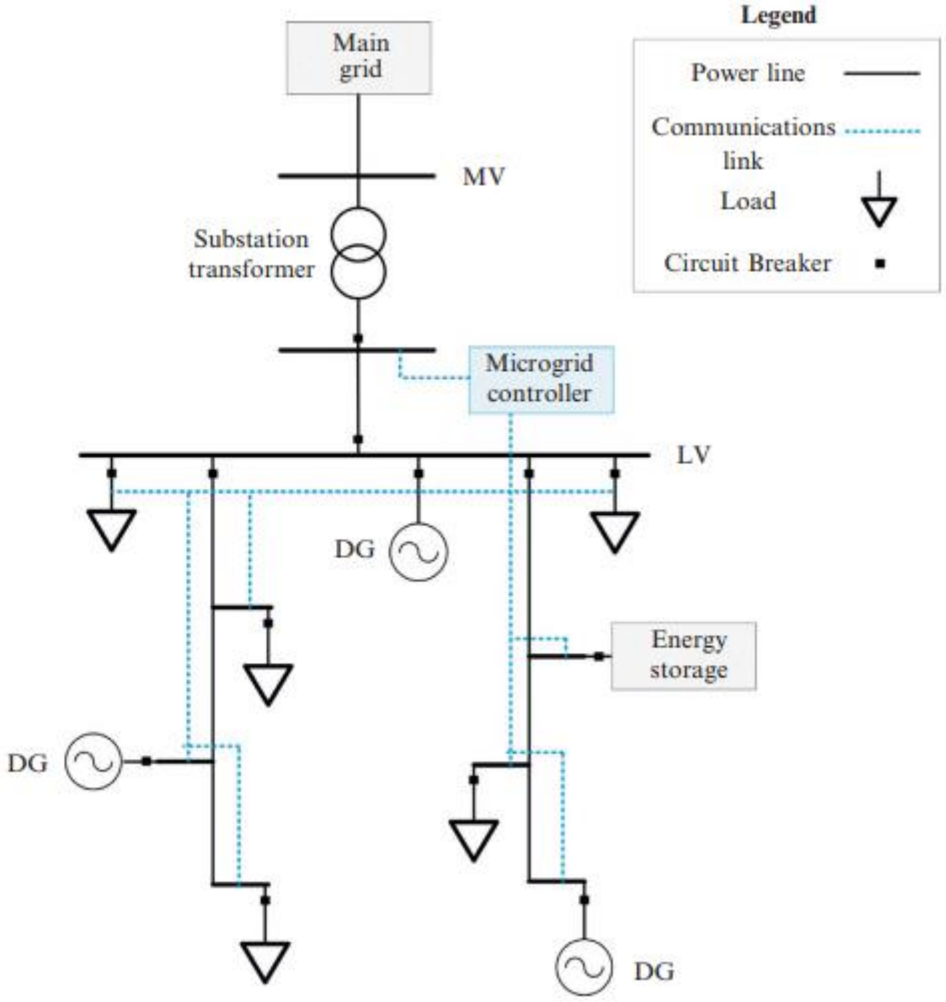

Figure 2 Single line diagram of a typical microgrid configuration [12]

Microgrids are a beneficial component of the electrical power system, beyond and behind the meter. It has been identified as a key component of Smart Grids (SG) for improving power reliability and quality, increasing system energy efficiency, and providing the possibility of grid-independence to individual end-user sites. The benefits of microgrids can be:

- Enabling grid modernization and integration of multiple SG technologies;
- Enhancing the integration of DER;
- Meeting end-user needs;
- Supporting the macrogrid.

As said in [13], a microgrid can be categorized for its size and capacity, types of assets, primary operating mode and point of interconnection. This approach makes it simple to perceive the microgrid business model and its main role.

The challenge of the microgrid will be the operation where it is disconnected from the main grid. This will depend on the type of distributed generation and loads, what type of energy storage system is connected to the MG, etc. The islanded operation brings new challenges of control and protection. These are topics that must be studied with different approaches of the ones used on traditional electrical grids.

### 2.2.2. DISTRIBUTED GENERATION

Distributed generation is characterized by producing electricity, by using renewable energy sources, fuel cell and alternative motors, and producing heat with cogeneration plants, across the distribution grid.[14] All these are operated by independent power producers, concession companies and end-use consumers.

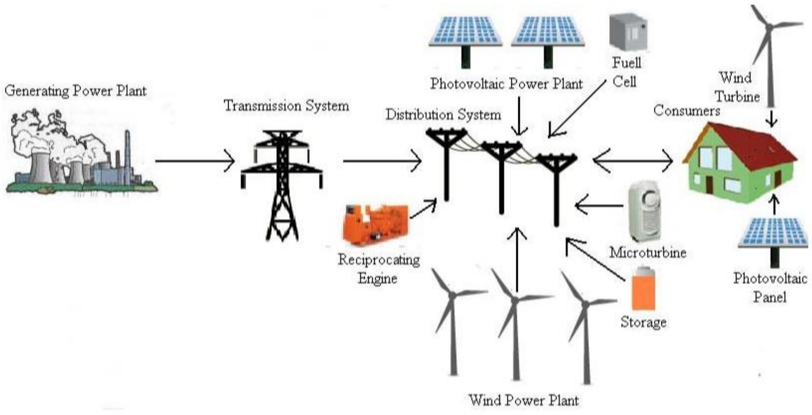

Figure 3 Example of various distributed generation in a bidirectional distribution system [15]

The motivation for this kind of generation is due to environmental protection, grid reliability and assist or be the source of energy in places where the generation by traditional methods is not possible [16]. Also, the fact that the generators are closer to the end-user brings benefits such as reduced energy transit and avoiding or postpone new investments in the distribution grid.

Reliability is becoming an issue due to the increasing of information technology systems, along the grid. These systems are more sensible to electricity interruptions and voltage sags. By introducing the distributed generators (closer to the electrical loads), reliability increases from 99,9% to 99,9999%, accordingly to [14] and [16].

Distribution grids usually have a radial structure and are conceived to be unidirectional when it comes to transport electrical energy [17]. This changes when DG is connected to these grids. When consumption is low, compared to the generation, power flow will reverse in the common couple points that are the interface with the transmission grid. These can bring problems such as conductors' current capacity and circuit breakers short-circuit breaking capacity exceeding their limits. This because of voltage variation when the decentralised generator connects or disconnects from the grid. To solve these problems, the variation in the common couple point must be null, therefore reactive power must be consumed and also maintaining balance with active power, in order to maintain voltage quality parameters.

Power electronics, used in power inverters and on asynchronous generators (for reactive power control), cause another problem when connected to the grid, that is the harmonic distortion [18]. This can be solved by applying filters and control mechanisms in order to minimize harmonic pollution. Some of these methods are approached in [17], [19].

### 2.2.3. SMART GRIDS

Smart grids are defined as being an electrical grid that has more automation, more sensors and control capabilities, more flexibility and efficiency than a traditional one [20]. It started when electrical grids started to have more renewable energy sources coupled to it and a necessity to management and control to provide a stable electrical grid was necessary, as seen in the last section.

Therefore, as microgrids and, consequently, deployment of distributed resources is increasing, management and control devices had to become smarter. In order to do that, intelligent electronic devices (IEDs) have been deployed throughout the grid [21]. They receive data from the sensors and can control equipment such as circuit breakers, on load tap changers and capacitor bank switches.

According to [22], the Department of Energy of the United States of America defines smart grids obeying six parameters:

- Enables informed participation by customers so that consumers can become an integral part of the electrical power system;

- Accommodates all generation and storage options, including all distributed energy resources;

- Enables new products, services and markets, managing independent grid variables such as energy, capacity, location, time, rate of change, and quality;

- Provides the power quality for the range of needs of different end-users;

- Optimizes asset utilization and operating efficiency, increasing the efficiency of maintenance procedures, decreasing losses and controlling congestions;

- Operates resiliently to disturbances, attacks, and natural disasters, reacting to such events isolating the faulted elements and keeping normal operation in the rest of the system.

The proliferation of distributed energy sources and prosumers (consumers with local active sources of electric energy generation and energy storage) obliges electrical grids to be in permanent communication and to adopt new technologies and applications, such as procedures based on big data and Internet of Things techniques [23] [24]. Real time control and performance monitoring is an important step to operate the distribution system reliably and cost effective, while accommodating profit-maximizing or cost minimizing incentives.

### 2.2.4. ENERGY HUBS

The evolution of distribution grid, with an increase of distributed resources and more autonomous capability, brings new concepts for energy distribution. One that is becoming more popular is the energy hubs.

Energy hubs are considered by [25] a unit where multiple energy conductors can be converted, conditioned and stored. It represents an interface between different energy infrastructures and loads.

Figure 4 is an example of an energy hub. It consumes energy from the infrastructures that it is connected to (in this example, electricity, natural gas, heat and wood) and provides energy services such as electricity, heating or cooling. In the hub, energy is converted using combined heat and power technology, transformers, power electronic converters, compressors, heat exchangers, etc. In other words, taking for example Figure 4, the electrical load can consume all of the energy it needs from the electricity input or can level it with natural gas.

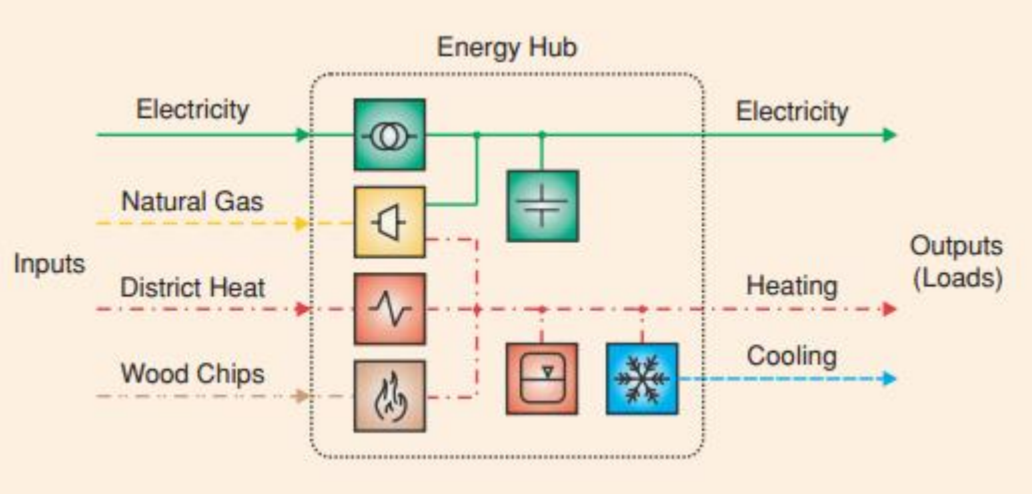

Figure 4 Diagram of an of an Energy Hub [25]

The two most important benefits of energy hubs are reliability and optimize the hub supply based on cost, emissions, availability, and others. Also, natural gas consumption is increasing in the electric power section and combined heat and power technology is largely implemented in the electrical grid due to its efficiency [26], [27]. This only benefits the implementation of energy hubs.

Energy storage can play an important role in this type of energy distribution system since it enables affecting the corresponding power flows. It enhances reliability, security, and availability, reducing energy costs and emissions.

## 2.3. ENERGY STORAGE SYSTEMS

### 2.3.1. ENERGY STORAGE TECHNOLOGIES

There are several technologies that can be used to store energy. The International Electrotechnical Committee (IEC) divides these technologies as shown in Figure 5.

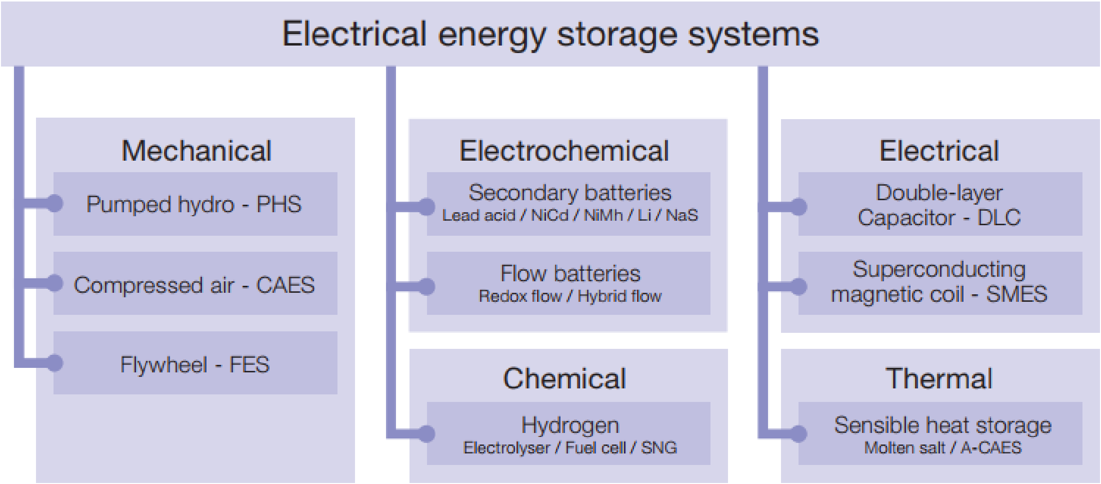

Figure 5 Energy Storage Technologies classification [28]

In this section, all the technologies will be addressed in the following subsections.

#### 2.3.1.1. MECHANICAL

##### 2.3.1.1.1. FLYWHEEL ENERGY STORAGE SYSTEM

Flywheel Energy Storage System (FESS) uses electrical energy to store kinetic energy and when electricity is needed, it uses the stored kinetic energy to produce electrical energy [29]. Flywheel technology is composed by a rotor that spins when powered by electrical energy. When a power failure occurs, the rotor continues to spin, due to inertia, and so the generator connected to it continues generating electrical energy.

##### 2.3.1.1.2. COMPRESSED AIR ENERGY STORAGE

Compressed Air Energy Storage (CAES) is a technology that stores energy by compressing ambient air or other type of gas and store it in a tank. It uses electricity to do such action. When there is a need for electrical energy, the gas in the tank is heated, which causes the air to expand. This expansion takes place on a turbine, which is connected to a generator that rotates and enables the generator to produce electrical energy. There are two methods for compressing the air, one is adiabatic and the other one is diabatic [30].

##### 2.3.1.1.3. PUMPED HYDROELECTRIC STORAGE

The principle behind Pumped Hydroelectric Storage (PHS), to store energy is to store water in a higher ground and taking advantage of the potential energy that is created when the water drops from the place where it is stored to the natural course of the river[31].

In order to store the water a water pump, powered by electrical energy, is required. This is usually done in off-peak hours. When electrical energy is required, the water in the upper reservoir is released. This water goes through a turbine that is connected to a generator that in its turn generates electrical energy.

#### 2.3.1.2. ELECTROCHEMICAL

##### 2.3.1.2.1. BATTERIES

A battery consists in multiple cells (usually in series) that can store chemical energy and converting electrical energy into chemical energy and vice-versa, via electrochemical reactions. Each cell is composed by an anode and a cathode, when submerse by an electrolyte and an electrical current is applied, ions move between the electrodes (anode and cathode). The movement of the ions defines the state of charge or discharge of the battery. The materials of which the electrodes and the electrolyte are made vary, and that is what defines the battery technology [32].

There are plenty of battery technologies but the most used and commercialized, until this moment, are the following:

- Lithium-Ion Battery;
- Lead-Acid Battery;
- Flow Battery.

The scope of this work, in regard to the technology used for energy storage system dimensioning, it will be used lithium-ion batteries.

#### 2.3.1.2.1.1. LITHIUM-ION BATTERY

Lithium-Ion (Li-Ion) batteries follow the same principle as other batteries when it comes to store energy. As previously said, batteries are composed by cells and these cells are composed by electrodes (anode and cathode) and an electrolyte. In Li-Ion batteries, the cathode contains some lithiated metal oxide and the anode is made of carbon material [33].

When the battery is being charged, lithium electrons, in the cathode, become ions and move, through the electrolyte, to the anode, where they combine with the carbon where they become deionized, and so electrical energy is transformed in chemical energy that is stored. When the battery is being discharged, the process, described before, is reversed. This process is illustrated in Figure 6.

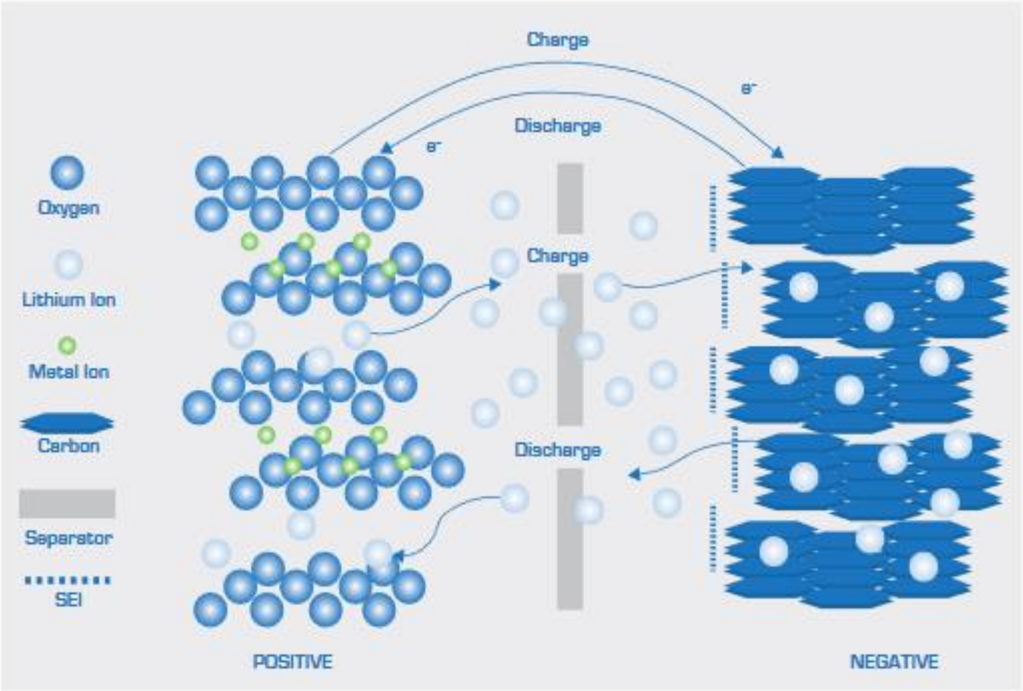

Figure 6 Charge/discharge principle of Li-Ion battery cell [34]

### 2.3.1.3. CHEMICAL

#### 2.3.1.3.1. HYDROGEN STORAGE SYSTEM

This technology uses electrolysis of water in order to separate the oxygen and the hydrogen (atoms that composes water). The oxygen is released to the atmosphere and the hydrogen is stored. To obtain electric energy from the stored hydrogen, a re-electrification combined with an oxygen injection is needed. The re-electrification process can be made using gas turbines, engines or fuel cells [32].

#### 2.3.1.4. ELECTRICAL

##### 2.3.1.4.1. DOUBLE LAYER CAPACITORS

Double layer capacitors or ultracapacitors can store electrical energy using two carbon electrodes involved by an electrolyte. The two electrodes create an electrostatic effect that enables the storage of electrical chargers between the electrodes, therefore store electrical energy [32].

##### 2.3.1.4.2. SUPERCONDUCTING MAGNETIC-COIL

Superconducting magnetic coil stores electrical energy by creating a magnetic field. This is possible when an electrical current passes through the coil. The material used to make the coil is one with very low resistance, so that the power losses could be almost zero[32].

This energy storage system needs a dedicated cooling system (usually liquid nitrogen) to maintain the coil material superconductive. It also needs a power converter (AC/DC or DC/DC) to control the current flow that allows it to charge and discharge.

#### 2.3.1.5. THERMAL

##### 2.3.1.5.1. PUMPED HEAT ELECTRICAL STORAGE

This technology uses electrical energy to, through a heat pump, exchange heat between two recipients (from “colder” one to the “hot” one). When the heat pump does the reverse process, becoming a heat engine, it produces mechanical work that makes the generator to produce electricity [35].

##### 2.3.1.5.2. LIQUID AIR ENERGY STORAGE

Energy storage through liquid air uses electrical energy to cool the air to a liquid state, storing it in a container. When electricity is needed, the liquefied air is heated to the gaseous state that turns a turbine and thus produces electrical energy [36].

## 2.3.2. GRID APPLICATIONS

### 2.3.2.1. POWER QUALITY

Power quality is defined by the guarantee, at satisfactory costs, of the proper, safe, and reliable functioning of consumer processes and equipment and of the supplying electrical system. This process involves ensuring continuity of service, the voltage and current waveform at any point in the electrical network must be sinusoidal, the amplitude and frequency values of the voltage must remain within the pre-defined limits and the lag between voltage and current must be acceptable[37].

Energy Storage Systems are a very well-suited solution to resolve problems of power quality. For this specific application, the ESS must have a large capacity to smooth the power and improve the power quality [38].

An ESS control example is specified in [39] where the power quality is assured using frequency and active power readings.

### 2.3.2.2. ENERGY ARBITRAGE

Energy arbitrage is a concept quite simple to understand; consists in buying electrical energy in the off peak period, when it is cheaper, to sell it in the period when it is more expensive[40]. This means that the BESS owner will gain from market opportunity. In [41]–[44] is discussed the best scheduling using solar PV penetration, the impact of battery degradation and the viability on electricity markets.

### 2.3.2.3. LOAD FOLLOWING

This application needs a solution that is sensible to demand variation and reacts when it fluctuates, in order to maintain grid frequency (generation equal to demand) [45].

Renewable Energy Source integration takes advantage of a similar procedure as load following but it is sensible to the power output of RES. Due to its intermittence, power output could have a rapid change and ESSs can provide a certain dispatchability to renewables [46].

#### 2.3.2.4. EMERGENCY BACKUP

Energy Storage Systems are used to secure prioritized loads when a black out occurs. This application is the use of ESSs to restore an electrical system after a blackout [17].

In [47] a research on BESS for backup power is addressed for an optimal operation.

#### 2.3.2.5. PEAK SHAVING

The BESS is responsible for storing electrical energy when there is low demand in the electrical grid where the BESS is inserted and then releases the energy when there is a high demand. This reduces grid peaks and increases its capacity [48].

#### 2.3.2.6. SPINNING RESERVE

The spinning reserve is the capacity of production that can respond in ten minutes to an outage, unless it is a frequency-responsive spinning reserve, in that case it should respond in ten seconds [49]. This means that energy storage systems can be capable of storing energy and be able to respond on the times mentioned before, depending on the storage technology. It can also take advantage of excess production of RES in order to perform and be able to be considered a spinning reserve.

### 2.3.3. MICROGRID INTEGRATION

Microgrids are boosted with ESSs. It endows more reliability (voltage and frequency control), energy independence and potentializes renewable energy sources [11]. Nowadays, a typical configuration of a microgrid integrates energy storage, as illustrated in Figure 2.

One of the most important operation for an ESS, in microgrids, is the operation in off-grid – disconnected from the main grid. This means that the energy storage system is forming the grid (grid forming), it forms the voltage wave, controls the power flow, responds to loads, etc. The timing of connection and disconnection from the main grid should be done at the exact time. For this, it is fundamental the control of all the microgrid and the use of equipment that it is capable to respond quick enough to cope with the transition.

The off-grid operation highly depends on the power inverter in the ESS. This inverter is a product of power electronics and one of its characteristics is low inertia, especially when compared to a rotating machine, like diesel generators. This low inertia brings a quicker response to the grid variations and a lower short circuit current. The latter has a very high impact on sizing the grid protections, that are sized accordingly when connected to the main grid and when a rotating machine is forming the grid [17] [50].

Another important application of ESS in microgrids is power quality issues. Power quality is very important nowadays since the increasing penetration of nonlinear power electronic based loads. Any deviation of a pure sinusoidal can seen as a power quality problem (harmonics, interruptions and voltage deviation).

Harmonics are becoming a serious issue in MG. Accordingly to [51], 27% of all power quality problems are related to harmonic distortion. In the same article [51] it is proposed an harmonic compensation in microgrids.

### 2.3.4. BATTERY ENERGY STORAGE SYSTEM

A Battery Energy Storage System (BESS) is a system ready to store energy and deploy such energy into the electrical grid when needed. For this to be possible, multiple components must work simultaneously, management and control should be perfectly integrated and proper protection must be considered [52].

This section will be divided into three major topics, in order to properly explain this type of systems. The first will be the energy storage system, the second will be the power conversion and control system and the last one the grid connection.

#### 2.3.4.1. BATTERY SYSTEM

The ESS is composed by the technology chosen to store energy (in this work, Li-ion batteries), but also composed by a fire protection system and by a cooling system.

The battery system is divided by cabinets, that can be plugged in parallel with each other. Each one has battery modules that have temperature and voltage sensors and the capability to communicate such values to another component, the battery management system (BMS). The BMS aggregates all information transmitted by the battery modules and is capable of communicating all data to a superior management system and give certain commands, for safety reasons, to the protection module [53]. This protection module must exist in each cabinet. It allows load break switching and protection of each cabinet, normally by the fuse.

The battery management system also tracks the state of charge (SoC) – capacity that is currently available as a function of the rated capacity [54] – state of health (SoH) – is defined in [54] as the fraction between the battery maximal releasable capacity and the rated capacity, in other words, it is an analysis of the battery degradation.

The information given by the BMS is crucial to optimize the lifetime of the battery. This is possible by optimizing the depth of discharge (DoD) – determined as the capacity in amper-hours that discharged from a fully charged battery divided by nominal battery capacity [55].

A cooling system is a very important aspect in ESSs. In the process of charge and discharge, heat is dissipated from each cell in each battery module. Normally, the batteries are stacked in a confined space, so the heat produced by the batteries stays in battery and in the room. If the heat in the batteries does not dissipate, efficiency starts to drop, and the battery starts to be more instable. If the system continues to operate, in these conditions, a fire will start.

With the risk of fire being a possibility for these systems, it is very important that the detection of such incident, is done as soon as possible. Thus, the fire protection system is one important aspect, as well, to be a part of the ESS. The gas chosen to extinguish the fire should be properly dimensioned for the technology that is in use, on the battery.

#### 2.3.4.2. POWER CONVERSION AND CONTROL SYSTEM

Power electronics are a fundamental piece in modern electrical grids and are a fundamental component in a battery energy storage system. The electrical current, in a battery, flows consistently in one direction – direct current (DC). The electrical grid works with alternating current (AC), that is a type of electrical current, in which the direction of the flow of electrons switches back and forth at regular intervals or cycles (frequency). With different types of electrical current, between the batteries and the grid, a power inverter is necessary to convert AC in DC and vice-versa. This equipment uses power electronics, such as insulated gate bipolar transistors (IGBTs), to do the conversions of electrical current [56]. An example of an AC-DC converter is illustrated in Figure 7. Six IGBTs are connected to a three-phase voltage supply, this configuration allows to filter only the positive side of each phase sinusoidal waves. That alone will not be sufficient to have DC voltage, therefore a DC converter is put in parallel to smooth the waves and become a constant voltage output [57].

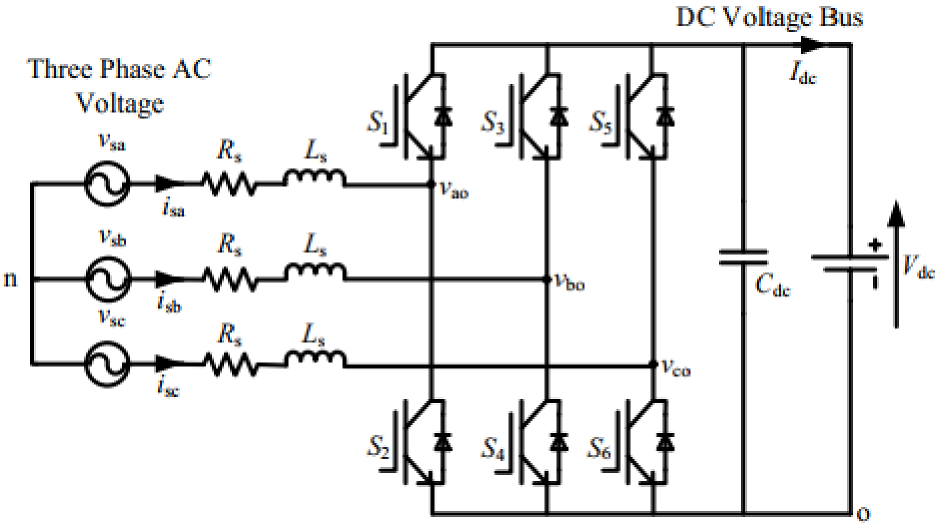

Figure 7 Example of a three-phase bidirectional AC-DC converter simplified schematic [57]

Therefore, power inverters allow the batteries to charge using the electricity availability of the electrical grid, in which the system is connected, and to discharge the batteries to that same electrical grid [57].

Controlling and management of BESSs components is essential to the operation of the system. A central unit of control should exist in order to receive the status of the main components. This unit must have a logic programmed in order to operate the system autonomously and in a secure way.

The control logic of this systems varies depending on the application, the size (power and energy), the grid connection, the type of the electrical grid that is inserted on, etc. That is why it is an important part of the system. This logic will define when is the right moment to charge, to discharge, what rate of charge/discharge, at what time, etc. To do this, the system must have a management system. A component that gathers all the information available and transmits it to the control unit when it needs it.

Protection is the main component in every electrical system, everywhere across the electrical grid, from generation until the end user. For battery energy storage systems is no exception. In these systems, two types of protection should be considered, one for AC circuits and another to DC circuits. For both, bidirectionality is a must have and should be one of the main restrictions when sizing it.

The main difficulty is dimensioning protections to DC circuits. These direct current protections must cope with the DC voltage of the battery cabinets. In batteries there is a voltage range, that depends on the battery state of charge.

#### 2.3.4.3. GRID CONNECTION

BESSs can be connected, to the electrical grid, in medium voltage (MV) or in low voltage (LV) depending on the application, site and the size (power and energy) of the system.

Some applications can have the need of a power transformer. Usually, because the power inverter normally has a three-phase distribution with no neutral and the loads that the ESS is gone to feed are not balanced, therefore there is the need for a neutral distribution. Also, when the BESS has to connect to the medium voltage electrical grid, there is the need of a step-up transformer to scale from LV to MV. The latter also need medium voltage switch gear to proper connect to the MV grid.

Depending on the application, there must be different concerns and cautions when sizing protections. The most difficult for protection sizing is when the system can work off-grid. In this case, the short circuit current can be drastically lower than when it is connected to the distribution grid, for the reasons explained in 2.3.3.

## 2.4. ELECTRIC MOBILITY

### 2.4.1. ELECTRIC VEHICLES

Electric mobility is expanding and gaining popularity in recent years. This is due to the increase of electric motioned vehicles more commonly known as electric vehicles. In [58] is stated that at the end of 2018, there were 300 million two/three-wheelers on the road and 5,1 million cars moved by the power of electricity. Figure 8, clearly illustrate and the ascending of this type of vehicles in the transportation sector.

The argument best known for the usage of EVs is that they pollute less than their counter part, the internal combustion vehicle (ICV). The comparison, for the purpose of comparing how much each one pollutes, is done by measuring the emission of carbon-dioxide to the atmosphere. It is expected that by 2030 there will be a reduction of 1 giga ton of CO2 emission [59], resulting from the exchange of internal combustion vehicles by electric vehicles.

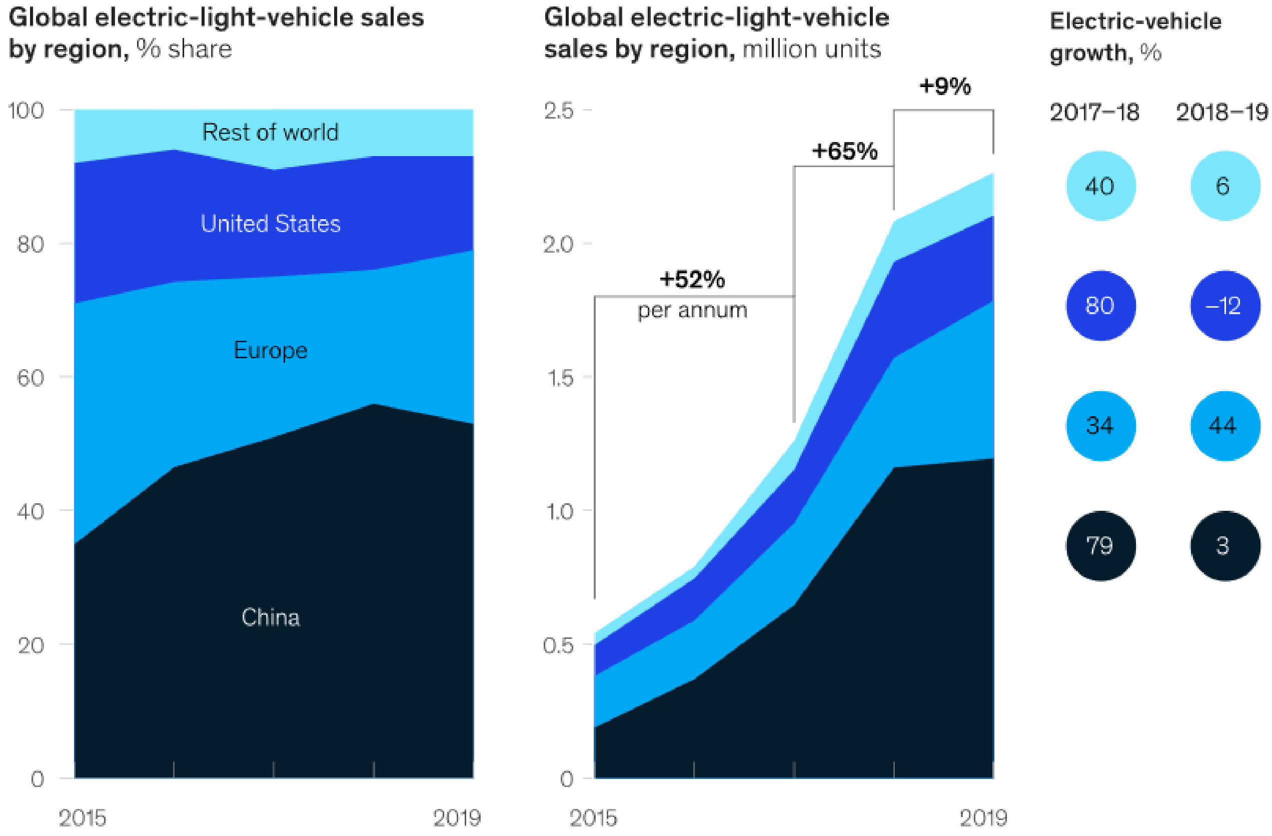

Figure 8 Electric car sales and market share, 2015-2019 [60]

In this work, only light duty vehicles will be addressed due to power and energy that is involved when considering the charge of these vehicles. This will be mostly battery electric vehicles (BEV) or plug in hybrid electric vehicle (PHEV).

### 2.4.2. ELECTRIC VEHICLE CHARGERS

Electrical vehicle chargers are very similar to power inverters. They can be inside or outside the vehicle. The charger must provide energy to the vehicle's energy storage system and that can be made in AC or DC power. When it is in AC the vehicle has the necessity of having a power inverter [61].

The international standard IEC 61851-1, classifies four modes of charging:

- Mode 1 is an AC connection (three or single phase), limited to 16 Ampère (A). The connection to the grid is done by a standard plug (must comply with the country standards). The vehicle battery charger (the power converter) is on the vehicle;

- Mode 2 is an AC connection, as in Mode 1, but the current intensity is now limited to 32 A and the cable must have protection and a pin for data exchange. The vehicle battery charger is on the vehicle;

- Mode 3 requires an electric vehicle supply equipment (EVSE), not exceeding 63 A, to connect the vehicle to the AC electrical grid. The connectors must have a group of control and signal pins in both ends of the cable. The vehicle battery charger is on the vehicle. This mode is usual for public charging stations;

- Mode 4 is characterized using off board chargers (the power inverter is outside of the vehicle). Therefore, the conversion is done inside the charging station and delivered in DC power onto the EV. This mode can reach 400 A DC;

### 2.4.3. IMPACTS ON THE ELECTRICAL GRID

Although EVs bring a new and greener perspective to the transport sector, they bring new challenges to the electrical grid. Electric power systems are designed to respond to instantaneous consumer demand (heat, light, etc) [62]. Therefore, the implementation of new electric loads will cause constraints of power and voltage congestion on these systems [63].

The charging of BEVs causes an increase of load demand and it is uncontrolled, meaning that the charging can occur during peak hours. Because of the multiple and simultaneous charging, the electrical grid components, sized for the previous load demand, have to handle the extra loads which can cause overloading and diminishing in the lifespan of such equipment.

Single phase chargers can cause phase unbalance by overload one of the three phases when EVs are charging in the same phase. This problem leads to voltage unbalance, caused by the current differences between the phases. In the interconnection points, the charger will originate voltage drops and deviation.

The power electronics on the chargers will generate harmonics, during the power conversion, this will cause a rise of the total harmonic distortion on the electrical grid where the chargers are connected.

The large power consumption leads to power losses on the distribution grid. In [64] it is said that power loss can reach 40% in the off – peak hours, considering that 60% of the vehicles are EVs connected to the distribution grid.

EV charging power demand changes according to the maker and model of the car and the state of charge of the batteries, upon arrival at the charging station. This is precisely what represents Figure 9 and Figure 10. In the first one, it can be seen the charging curve of a Renault Zoe, that according to Electric Vehicle Database [65] is one of the cheapest EVs in the market. Power demand never goes further than 45kW and when it reaches half charge starts to decline. The second graphic represents the charging curve of the Tesla Model 3 Long Range. This one has the possibility to be charged with two charging modes, which are represented in the figure. At maximum charging capacity it can achieve 150kW until it reaches 50 % starts to decline.

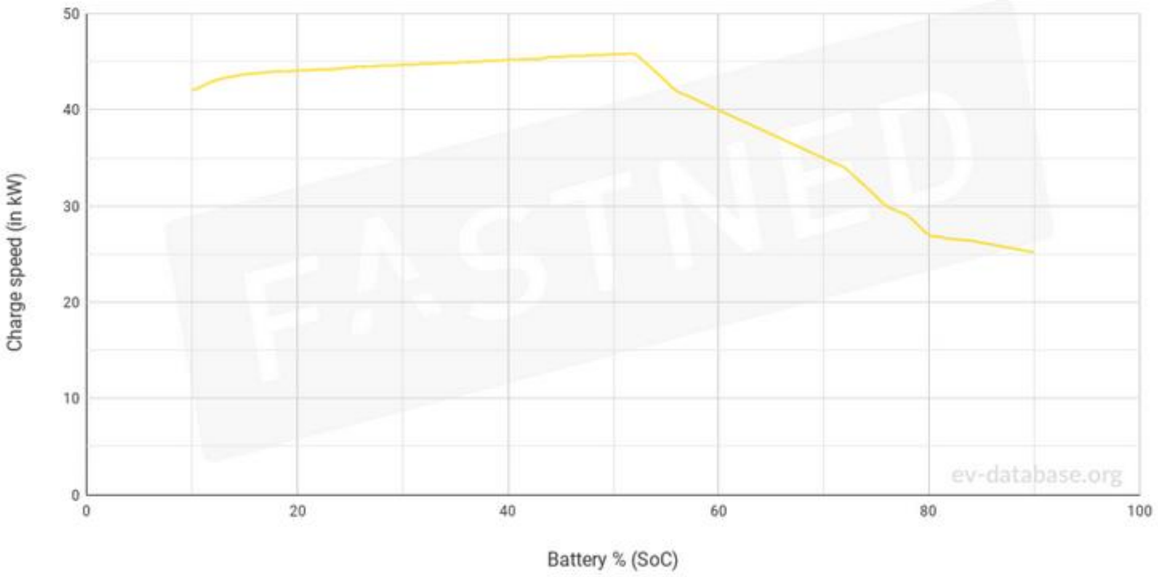

Figure 9 Renault ZOE charging power in order to its battery state of charge [66]

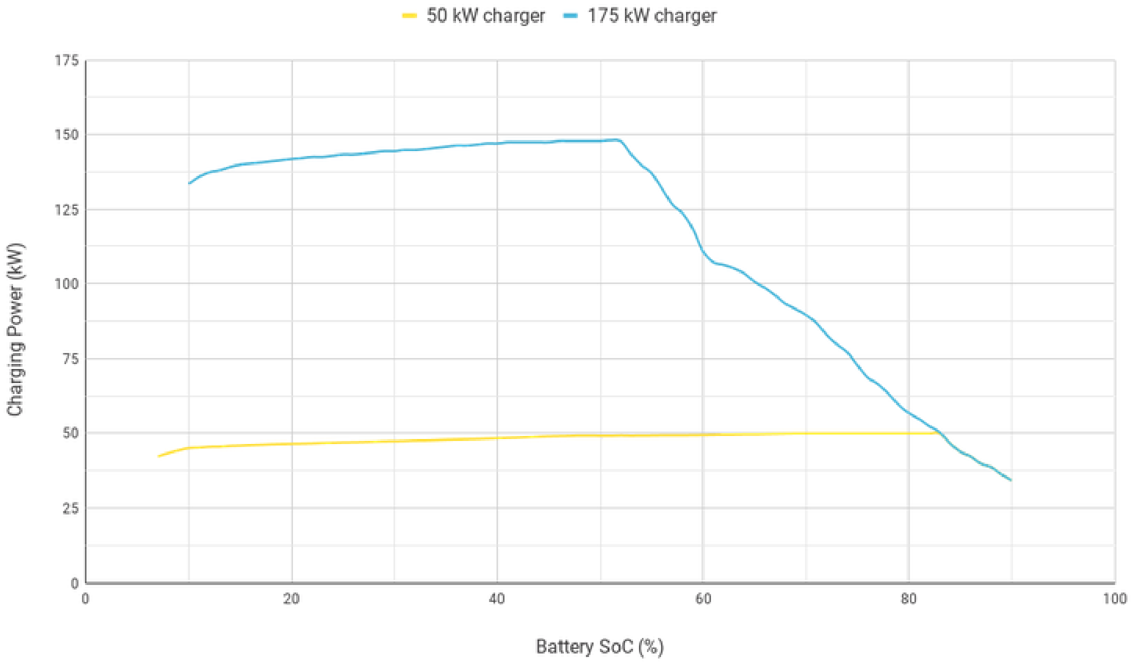

Figure 10 Tesla Model 3 Long Range charging power in order to its battery state of charge with two different chargers [67]

Most of the public charging points or condominiums charging points do not have the infrastructure to simultaneously charge an aggregate charging of these vehicles. Therefore, some solutions started to appear. Smart charging is one of them. This type of charging enables active control of loads and optimize certain objectives such as avoid transformers and lines saturation, exceed the contracted power, minimization of costs, etc [68].

This smart type of charging can have multiple applications. It can be applied in distribution grids, on condominiums and public charging points or applied in microgrids [69]. An extension of smart charging is to have bidirectionality. This feature, also known as vehicle to grid (V2G) allows vehicles to discharge their batteries for the electrical grid benefit, turning EVs into distributed energy storage systems, providing for example, ancillary services and regulation services to the grid [70] [71] [72].

Energy storage systems are also an approach to mitigate the peak power demands of electric vehicles charging, acting as a buffer. The future of EVs is devoted to increase its range and reduce charging time. This implies increasing power availability at the charging points [73]. This prevents upgrades to the distribution grid and if coupled with renewable energy sources potentialize its generation, charging the ESS with energy produced by RES and then discharge it when needed to the EV [74] [75].

## 2.5. LITERATURE REVIEW ON BESS OPTIMAL SIZING FOR FAST CHARGING INFRASTRUCTURES

Nowadays, it is becoming more common in the literature several models where researchers study the integration of renewable energy sources, energy storage technologies and electric vehicle charging infrastructure in urban areas [76]. As it was stated in the previous sections of this work there is a path to a smarter, and optimized sizing and control of each one of these subjects.

The problems listed in section 2.4.3 are being studied and are many solutions being proposed in literature. Most of them focus on optimized planning and management in order to minimize the impacts of EV charging in the electrical grid, mainly in the distribution network.

Planning and management are the fundamental part of smart charging of electric vehicles. This feature is integrated into the control and management system of the fast charging infrastructure and can be composed with various features since load forecasting, charging priorities, etc.

Another solution is the usage of the vehicles as mobile energy storage systems, also known as vehicle to grid (V2G). For this to work, the EV has to have the capability for bidirectional current flow when connected to the charger. Also, the charger has to have a bidirectional power converter. Thus, the charging infrastructure is able to balance power and energy, satisfying the electrical grid constraints. This solution is suitable when vehicles stay connected to the charging station for considerable periods of time.

According to [77], the majority of research point out that the most popular and advantageous system design to cope with the power demand of EV charging is having a RES and an ESS connected to the electrical grid and the charging infrastructure, as shown in Figure 11.

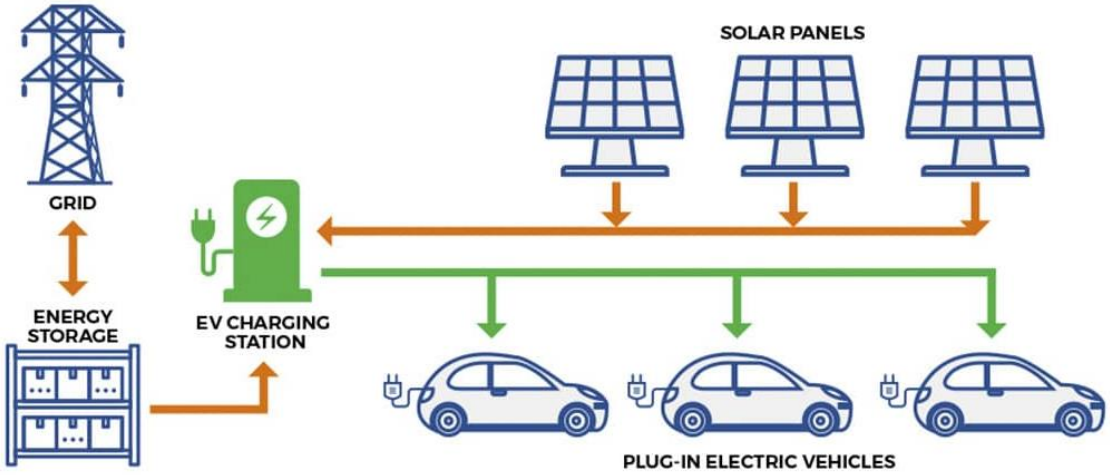

Figure 11 Design of an electric vehicle charging station integrating ESS and RES [78].

In [79], [80], a coordinated smart charging control scheme in a PV-BESS integrated EV charging station to regulate BESS operation in order to avoid transformer overload. The BESS is regulated for smoothing PV power output depending on the loading of transformer and PV availability. Grid services are also provided in these two articles. These grid services are also comprised in [81], where BESS is coupled in an EV charging station, comprised in a microgrid, to analyse power quality and load demand variations, paired with V2G technology.

A grid connected PV and BESS in a charging station optimization is proposed in [82] to determine the optimal sizing and energy management strategy with the objective of minimizing the cost of electricity. Also, in [83] a BESS is proposed to couple in a fast charging station to reduce connection fees and grid reinforcements costs. This paper uses a method for the energy management of charging station that delivers grid services in off-peak EV charging demand, sizing method that takes into account its ageing and an economic analysis for the trade-off between the BESS investment and contracted power.

In [84] [85], was proposed a particle swarm optimization algorithm to solve a photovoltaic (PV) energy source with an EV charging station and an ESS optimization problem. The objective function of [84] included charging cost and charge-discharge cycle limit of the energy storage system. In [85] was proposed an optimal capacity calculation procedure for distributed generation and ESS. In [86], a search-based algorithm was designed to determine the optimal number of photovoltaic panels and energy storage system capacity.

The main objective in [87] is to avoid exceed residential power demand peak, in order to do that it was used an ant colony optimization to determine the dynamic price of the charging station services, directing EV users to a scheduled charging. In order to minimize cost, a multi-target whale optimization algorithm was used in [88] to find the optimal configuration of a EV charging station with photovoltaic and energy storage system.

In [89], the Monte Carlo method was used to model the electric charging demand and renewable generation. The objective was to find the optimal solution that maximized the profit measured by its net present value. For that, it was used a genetic algorithm to optimize the installation and operation of the charging station.

For the purpose of this work an analysis and optimization sizing of battery energy storage system, in this system design was studied and developed a tool capable of sizing this kind of systems taking into consideration all of the restrictions of the other connected structures.

# 3. METHODOLOGY

In the scope of this master’s thesis, an optimization problem to minimize the implementation costs of a stationary energy storage system to buffer between the electrical grid and the electric vehicle chargers is addressed. In this regard, an optimization based on the interior point algorithm, where the objective is to minimize the costs of maintenance, operation, and installation of a BESS, while properly modelling the different resources is done.

The flowchart illustrated in Figure 12, gives an overview and explains how the methodologies, presented in the next sections, are connected and related to each other. Each one of the boxes has a letter which is then referred and detailed in the corresponding section.

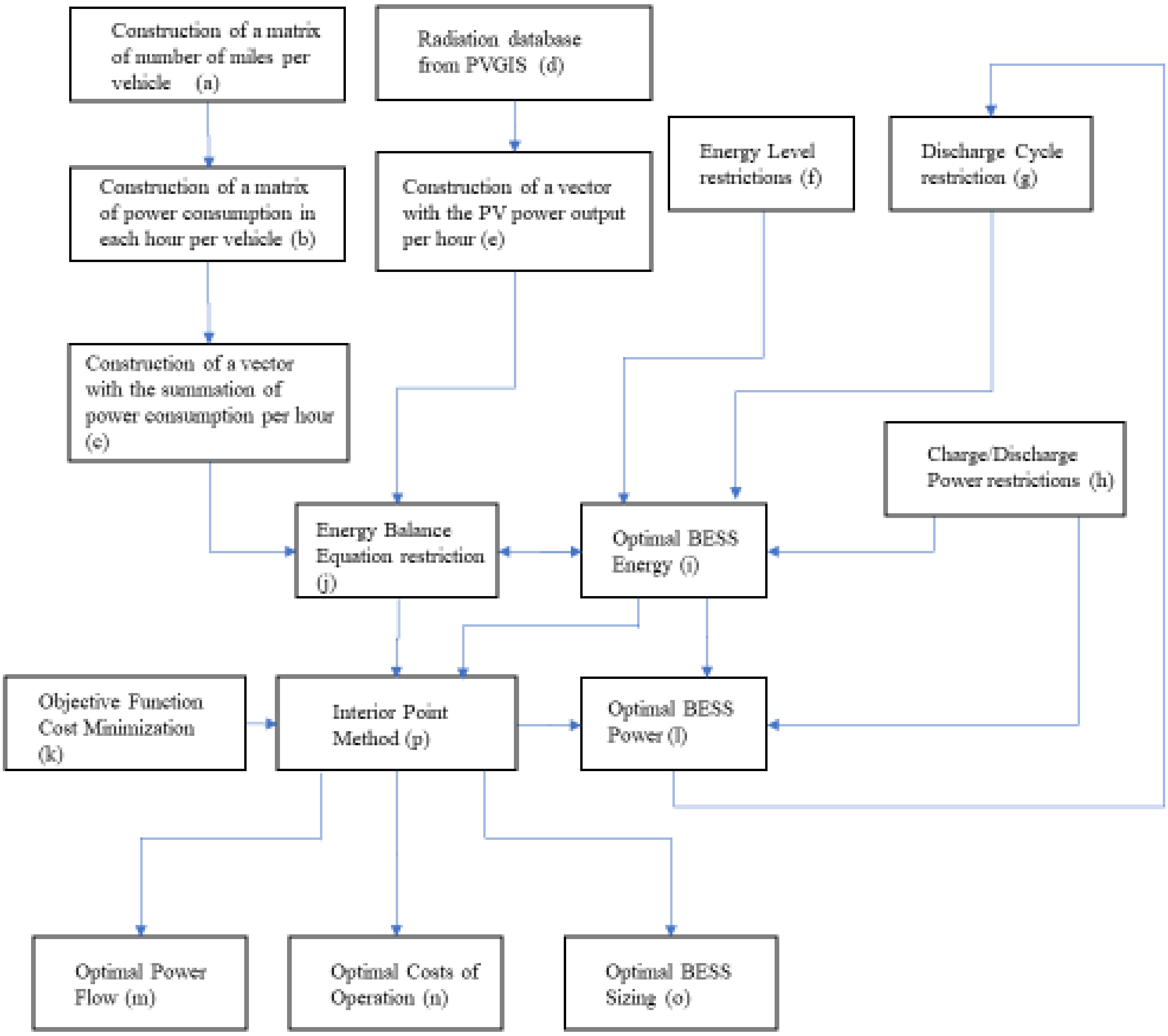

Figure 12 Methodology Flowchart

## 3.1. ELECTRIC VEHICLE CHARGING MODELLING APPROACH

In this section, a modelling approach for electric vehicle charging is purposed. In [90], a probabilistic approach taking into account the distance that an EV will do and the probability of being a car with a particular set of characteristics. For this work, a similar approach will be done.

In order to define the characteristics of the vehicles, five types were chosen to be assumed as the EV universe. Those characteristics are defined on Table 1. The chosen vehicle is defined in the beginning and it takes into consideration the probability associated with them, $Pr^k$ [91]. The other characteristics such as power, energy and range were based on [92].

Table 1 Electric Vehicle characterization

| $Vc^k$ | $P^k$ **(kW)** | $E^k$ **(kWh)** | $d^k_{max}$ **(km)** | $Pr^k$ |
|---|---|---|---|---|
| $Vc^1$ | 150 | 72,5 | 444 | 0,300 |
| $Vc^2$ | 45 | 52 | 314 | 0,295 |
| $Vc^3$ | 40 | 32 | 190 | 0,150 |
| $Vc^4$ | 75 | 46 | 190 | 0,130 |
| $Vc^5$ | 45 | 36 | 219 | 0,120 |

In [93] is defined that a vehicle day mileage has an exponential distribution, expressed by the equation (1) , where $x$ is the daily driving kilometers.

$$f(x) = 0{,}0296^{(-0.0296x)}, x \geq 0 \quad (1)$$

The average mileage of such vehicles is going to be considered instead of considering every short trip defined by the previous equation. The average mileage ($da$) is defined in equation (2) . The variable $d^k_{max}$ is the maximum possible miles by vehicle $k$.

$$da = \frac{d^k_{max}}{2} \qquad (2)$$

Equation (3) is the expression that gives the probability for the vehicle k going through the $da$ trip.

$$F(da) = \int_0^{d^k_{max}} f(x).dx \qquad (3)$$

In order to determine the expected mileage at each time instant, $d^k_a(t)$, is necessary to know the probability of driving at any time instant for each day, $g(t)$. This can be obtained in [90], which is translated in Table 5, that gives the vehicle trip distribution on weekdays and weekends in the United States. Therefore, by multiplying this probability by the probability obtained in (3), it is achieved the probability of driving at any time instant for each day, equation (4). This corresponds to (a) in the flowchart.

$$d_a^k(t) = g(t) \times F(da) \qquad (4)$$

The vehicle state of charge is calculated by equation (5), taking into account the previous state of charge and subtract the distance that the car covered in its trip. Assuming that an the beginning of every trip a SoC is always 100%.

$$SoC_i^k(t) = SoC_i^k(t-1) - \left( \frac{\int_{t-1}^{t} d_a^k . dt}{d_{max}^k} \times 100 \right) \qquad (5)$$

The energy that the vehicle has left, in its batteries, is calculated in equation (6). It is obtained assuming a direct proportion between the state of charge and the energy capacity of the EV.

$$E_{EV} = \frac{E^k \times SoC_i^k(t)}{SoC(0)} \qquad (6)$$

The energy that is needed to fully charge the vehicle is calculated in equation (7).

$$E_{EVC} = E^k - E_{EV} \qquad (7)$$

Assuming that the charging power, supported by the electric vehicle, stays the same through the charging, the time it takes to charge the vehicle can be calculated by equation (8).

$$\Delta t = \frac{P_{EVC}}{E_{EV}} \qquad (8)$$

The charging power has a very simple restriction, translated by the system of equations (9). If the charging power limit of the EV is lower than the maximum power output of the charger, the power considered should be equal to the vehicle power limit. If not, the charging power must be equal to the power output of the charger. This corresponds to (b) and (c) in the flowchart.

$$\begin{cases} P_{EVC} = P^k & se\ P^k \leq P_{ch} \\ P_{EVC} = P_{ch} & se\ P^k \geq P_{ch} \end{cases} \qquad (9)$$

## 3.2. PHOTOVOLTAIC ENERGY GENERATION MODELLING APPROACH

The photovoltaic energy generation is modelized by equations (10) and (11).

Equation (10) refers to the power generated by the photovoltaic panels in the moment t, $P_{pv}(t)$. $G(t)$, is the solar radiance at the time period t, given by the Photovoltaic Geographical Information System (PVGIS) interactive tool. The dataset has the hourly solar radiation for the year 2015, with optimize slope and azimuth, and for a fixed mounting type. The localization was set to the north of Portugal. $A$ is the total area covered by the PV panels, in square meters ($m^2$) and $\mu_{pv}$ is the system efficiency. This corresponds to (d) in the flowchart.

$$P_{pv}(t) = G(t) \times A \times \eta_{pv} \qquad (10)$$

Equation (11) refers to the energy obtained from the photovoltaic panels, $E_{pv}(t)$, in the moment t, that can be used to feed the electric vehicle charging station, sold to the connected electrical grid or to store in the energy storage system. This corresponds to (e) in the flowchart.

$$E_{pv}(t) = \int_{t_1}^{t_2} P_{pv}(t).dt \qquad (11)$$

## 3.3. ENERGY, IMPLEMENTATION AND MAINTENANCE COSTS

The energy prices are the ones defined by ERSE that respect their time periods and costs difference between low voltage and medium voltage delivery.

The efficiency of the system is translated in equation (12). Followed by the limits on the efficiency variables in (13).

$$\eta_{ESS} = \eta_{ST} \times \eta_{PCS} \qquad (12)$$

$$0 \leq \eta_{ESS} \wedge \eta_{ST} \wedge \eta_{PCS} \leq 1 \qquad (13)$$

The cost for the installation of the ESS is defined in (14). It is the summation between the costs of the power conversion system (15) and costs associated with the energy storage technology (16).

The latter two equations take into consideration the power of the system, $P_{ESS}$, and its nominal energy, $E_{nESS}$. The costs per unit of energy and power, $C€/_{kWh}$ and $C€/_{kW}$ , will have fixed values, as well as for the efficiency of the storage technology, $\eta_{ST}$.

$$c_{IESS} = c_{PCS} + c_{ST} \quad (14)$$

$$c_{PCS} = P_{nESS} \times \eta_{PCS} \times c€/_{kW} \quad (15)$$

$$c_{ST} = c€/_{kWh} \times \eta_{ESS} \times E_{nESS} \quad (16)$$

The maintenance of the ESS is considered in (17). This approach is based on [89]. It considers costs of installation (defined in the equations above, within this section) and the annual degradation defined by the variable $d_{ESS}$.

$$Mc = c_{IESS} \times d_{ESS} \quad (17)$$

## 3.4. ENERGY STORAGE SYSTEM MODELLING APPROACH

This section of the work describes the modelling approach for the energy storage system.

The charging process is defined in equations (18) and (19). First, it is necessary to define the charging power at each given instant, $P_{CESS}(t)$. The charging power is given by equation (18), as this equality can be assumed when periods of one hour are being considered. The variable $E_{ESS}(t)$ can assume positive and negative values, as it represents the charge and discharge energy values. This variable must have a lower or equal value when compared to the constant $P_{nESS}$ (19). This corresponds to (h) in the flowchart.

$$P_{CESS}(t) = E_{ESS}(t), \rightarrow E_{ESS}(t) \geq 0 \quad (18)$$

$$P_{CESS} \leq P_{nESS} \quad (19)$$

Equation (20) defines the energy level of the energy storage system at each period, where the energy level of the next period is the summation between the energy level of the current period and the energy charged between those periods. This equation is valid for the charging process. This corresponds to (f) in the flowchart.

$$El_{ESS}(t+1) = El_{ESS}(t) + \eta_{ESS} \times \int_{t_1}^{t_2} P_{CESS}(t).dt \tag{20}$$

The discharging process is defined in equations (21) and (22). First, it is necessary to define the discharging power at each given moment, $P_{DESS}(t)$. The discharging power is given by equation (22), as this equality can be assumed when periods of one hour are being considered. The variable $E_{ESS}(t)$ can assume positive and negative values, as it represents the charge and discharge energy values. This variable must have a lower or equal value when compared to the constant $P_{nESS}$ (22). This corresponds to (h) in the flowchart.

$$P_{DESS}(t) = -E_{ESS}(t), \rightarrow E_{ESS}(t) \leq 0 \tag{21}$$

$$P_{DESS} \leq P_{nESS} \tag{22}$$

Equation (23) defines the energy level of the energy storage system at each time period, where the energy level of the next period is the summation between the energy level of the current period and the energy discharged between those periods. This equation is valid for the discharging process. This corresponds to (f) in the flowchart.

$$El_{ESS}(t+1) = El_{ESS}(t) - \frac{\int_{t_1}^{t_2} P_{DESS}(t).dt}{\eta_{ESS}} \tag{23}$$

Equations (24) and (25) represent the limits of the energy level of ESS. These limits are defined between 10% ($Elmin$) and 90% ($Elmax$) of the nominal energy of the energy storage system. This corresponds to (f) in the flowchart.

$$El_{ESS} \geq Elmax \times E_{nESS} \tag{24}$$

$$El_{ESS} \leq Elmin \times E_{nESS} \tag{25}$$

## 3.5. OBJECTIVE FUNCTION AND PROBLEM CONSTRAINTS

The objective function of this optimization is minimizing total operational costs including the implementation of an energy storage system in an electric vehicle charging station. Equation (26) represents the objective function taking in consideration the costs with energy transactions, ESS investment costs and its life cycle. This corresponds to (k) in the flowchart.

$$\min cost = \sum_{t=1}^{T} \left(c_{PEG}(t) \times E_G(t)\right) + c_{IESS} + Mc \qquad (26)$$

Equation (27) translates the energy balance in this study. It contemplates the ESS charge/discharge process, the energy bought of the electrical energy provider and the energy demanded by the EV chargers as well as the energy produced by photovoltaic panels. This corresponds to (j) in the flowchart.

$$E_G(t) = E_{EVC}(t) + E_{ESS}(t) - E_{PV}(t) \qquad (27)$$

Equation (28) defines the nominal power of the energy storage system, given by maximum absolute value of $E_{ESS}$.

$$P_{nESS} = max|E_{ESS}| \qquad (28)$$

Equation (29) limits the number of discharge cycles ($N$) of the ESS. This condition is to maximize the longevity of the batteries. This corresponds to (g) in the flowchart.

$$\sum_{t=1}^{T} (Pdess\ (t) \leq N \times \eta_{ESS} \times E_{nESS}) \qquad (29)$$

## 3.6. INTERIOR POINT ALGORITHM

Interior point methods provide an alternative to active set methods for the treatment of inequality constraints. Accordingly to [94] most of the algorithms use sequential quadratic programming (SQP) ideas to handle nonlinearities in the constraints and the trust region strategies to allow the algorithm to treat convex and non-convex problems. This corresponds to (p) in the flowchart.

There has been much research in using interior point methods for nonlinear programming in [94]–[96]. In [94], is presented an interior point method for solving large nonlinear programming problems, by combining SQP and trust region methods. In [96] is presented and analysed a trust region method in order to solve nonlinear equality constraints optimization problems. In [95] is described an interior point method for nonlinear programming and discussed its software implementation and numerical performance.

The interior point method used in the MatLab solver, simplifies the original problem by using an approximation and creating another problem (simpler to solve). In this approximation is set as many slack variables as inequality constraints. The logarithmic term in [97], is called a barrier function.

The interior point approach to constrained minimization is to solve a sequence of approximate minimization problems.

The nonlinear problem of the form $min_x$ f(x), subject to $h(x) = 0$ and $g(x) \leq 0$, where $f\colon \mathbb{R}^n \longrightarrow \mathbb{R}$, $h\colon \mathbb{R}^n \longrightarrow \mathbb{R}^l$ and $h\colon \mathbb{R}^n \longrightarrow \mathbb{R}^m$ are twice continuously differentiable functions, is replaced by a sequence of the subproblems of the form

$$min_z \, \Psi_\mu \, (\mathrm{z}) = f(x) - \mu, \sum_{i=1}^{m} \ln(s_i)$$

subject to $h(x) = 0$ and $g(x) + s = 0$

Here $s > 0$ is a vector of slack variables, $s_i$, $\mu > 0$ is the barrier parameter and $z = (x, s)$. The number of slack variables, $s_i$, is equal to the number of inequality contraints $g$. As $\mu$ decreases to zero, the minimum of $\Psi_\mu$ (z) should approach the minimum of $f$. This approximate problem is a sequence of equality constrained problems which are easier to solve than original problem.

In order to solve the new problem, the algorithm uses one of two steps at each iteration:

1. Direct step – this step is the first one to be tried. This step is also called Newton Step and attempts to solve Karush-Kuhn-Tucker (KKT) conditions, $\nabla_x L(x\,,\lambda)$ =0 and $\lambda_{g,i}\, g_i(x) = 0 \;\forall\, i$ . The Lagrangian function is defined by $\mathrm{L}\,(\mathrm{z}, \lambda\,, \mu) = \Psi_\mu\,(\mathrm{z}) + \lambda_h^T h(x) + \lambda_g^T g(x + s)$ where $\lambda = (\lambda_h\,, \lambda_g)$ are Lagrange multipliers. The KKT equations are solved using a linear approximation $\begin{bmatrix} H & 0 & J_h^T & J_g^T \\ 0 & S\Sigma & 0 & -S \\ J_h & 0 & I & 0 \\ J_g & -S & 0 & I \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta s \\ \Delta\lambda_h \\ \Delta\lambda_g \end{bmatrix} = - \begin{bmatrix} \Delta f - J_h^T . \lambda_h - J_g^T . \lambda_g \\ \mathrm{S}\lambda - \mu\mathrm{e} \\ \mathrm{h} \\ \mathrm{g} + \mathrm{s} \end{bmatrix}$, where $J_g$ and $J_h$ denotes the Jacobian of the constraint functions $g$ and $h$, respectively, $H$ is the Hessian of the Lagrangian of the $\Psi_\mu$ , $S = diag(s)$, $\Sigma = diag(\lambda)$ and $e$ is the vector of ones the same size as $g$. The solution for $(\Delta x, \Delta s)$ is obtained by $LDL$ factorization,

which allows the determination of whether the projected Hessian is positive definite or not; if not, the algorithm uses a conjugate gradient step.

2. Conjugate gradient step – this is the second step to be tried. It uses a trust region method. The algorithm obtains Lagrange multipliers by approximately solving the KKT equations. Then, the quadratic approximation to the approximate problem in a trust region is minimized, $min_{\Delta x,\Delta s} \nabla \mathrm{f}^T \Delta x + \frac{1}{2}\Delta x^T \nabla_{xx}^2 L \Delta x^T + \mu \mathrm{e}^T S^{-1} \Delta s + \frac{1}{2}\Delta s^T S^{-1} \Sigma \, \Delta s,$ subject to linearized constraints, $g(x) + J_g \, \Delta x + \Delta s, = 0,$ $h(x) + J_h \, \Delta x = 0.$ The norm of the linearized constraints are minimized inside a region with radius scaled by $R.$

Each iteration the algorithm decreases a merit function defined by $\phi_\eta(\mathrm{z}) = \Psi_\mu \, (\mathrm{z}) + \eta \| c(z \|,$ with $c(z) = (h(x), g(x) + s).$

The parameter $\eta$ may increase with iteration number in order to force the solution towards feasibility. If it does not decrease, the algorithm rejects the attempted step and attempts a new one.

The optimization process is done by using the Interior Point Algorithm from the solver fmincon in MatLab. This solver is a method of the Optization Toolbox and are based on trust regions. The choice to use such method was to find a solution on constrained nonlinear problem.

# 4. CASE STUDY ON THE INTEGRATION OF BESS IN A FAST CHARGING STATION

The case study is composed by four different fast charging stations infrastructures. The variations between the four of them dwell on the power supplies connected to the infrastructure.

One depends exclusively on the electrical grid, a connection to the distribution system. The second one has a photovoltaic generation. The last two have a Battery Energy Storage System connected to the same electrical connection point of the distribution system and of the PV generation. The difference between the two BESS integration scenarios is the photovoltaic generation. One of them has it and the other does not.

The scope of the case studies is to compare the energy cost savings between the four scenarios and the operation costs of the fast charging infrastructure. This approach sizes a stationary energy storage system with lithium-ion technology batteries through a co-optimization of the planning and operation stages

The simulations were performed taking in consideration the methodologies presented in chapter 3. The time series is defined by the hour and the optimization is done for each week.

## 4.1. BEV FAST CHARGING INFRASTRUCTURE TOPOLOGY COMPARISON

### 4.1.1. BASELINE SCENARIO

The baseline scenario is illustrated in the single line diagram, in Figure 13. It has a medium voltage connection and ten BEV fast chargers, with a power rate of 50kW each.

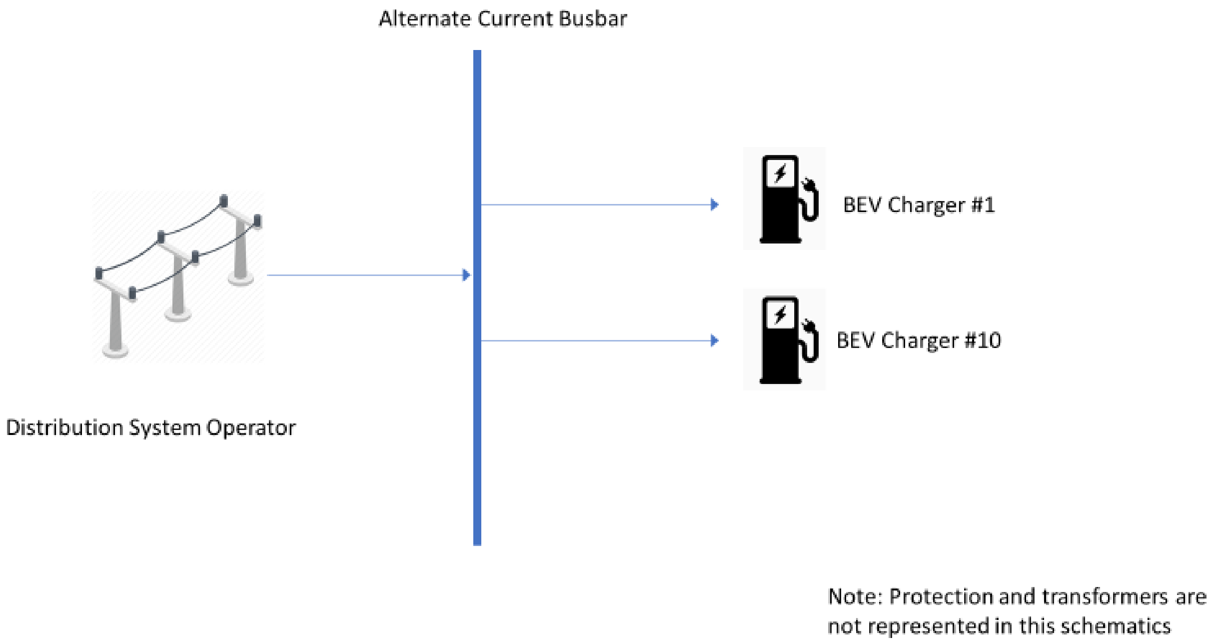

Figure 13 Baseline Scenario Schematic

For this scenario, the operator of the charging station decided to install ten chargers and requires that all vehicles must charge at maximum power, either limited by the vehicle or the charger.

In order to establish a load power demand, it was used the modelling approach described in 3.1. The typical load consumption of the auxiliary services of the charging infrastructure was added to the EV charging power load.

The maximum power demand obtained was 580kW. Therefore, the contracted power and the installed power should be higher. There was no limit imposed but the contracted power is a decision variable of the optimization.

The baseline scenario serves as the comparison point to the other scenarios and it will be compared to the other three in order to see the impacts that the renewable energy source and the BESS have in these installations.

In the Figure 14 it is illustrated the power consumption on a day of the year analysed

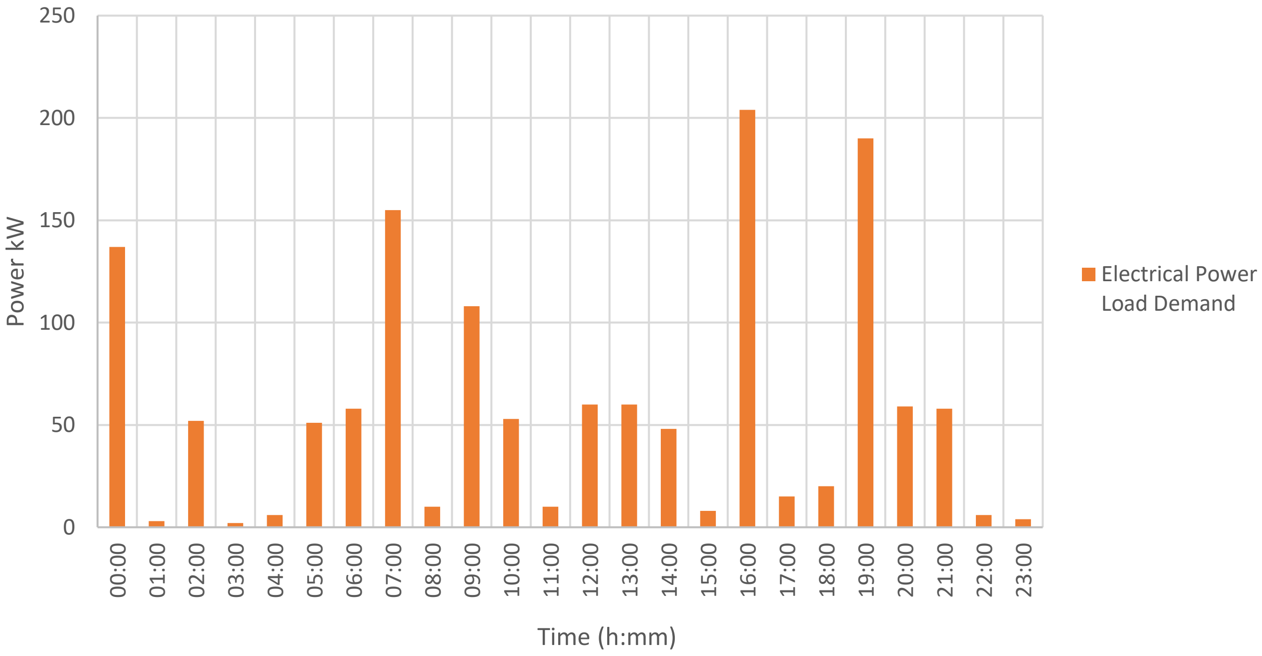

Figure 14 Fast Charging Station load diagram on a day of the year analysed

### 4.1.2. RENEWABLE ENERGY SOURCE INTEGRATION SCENARIO

The second scenario integrates a RES to the BEV Fast Charging Station. The renewable energy source is a photovoltaic generation with 500m$^2$ of area of panels previous installed. The cost of the PV installation is added to the operational costs but is not considered as an investment. This scenario one-line diagram is shown in Figure 15.

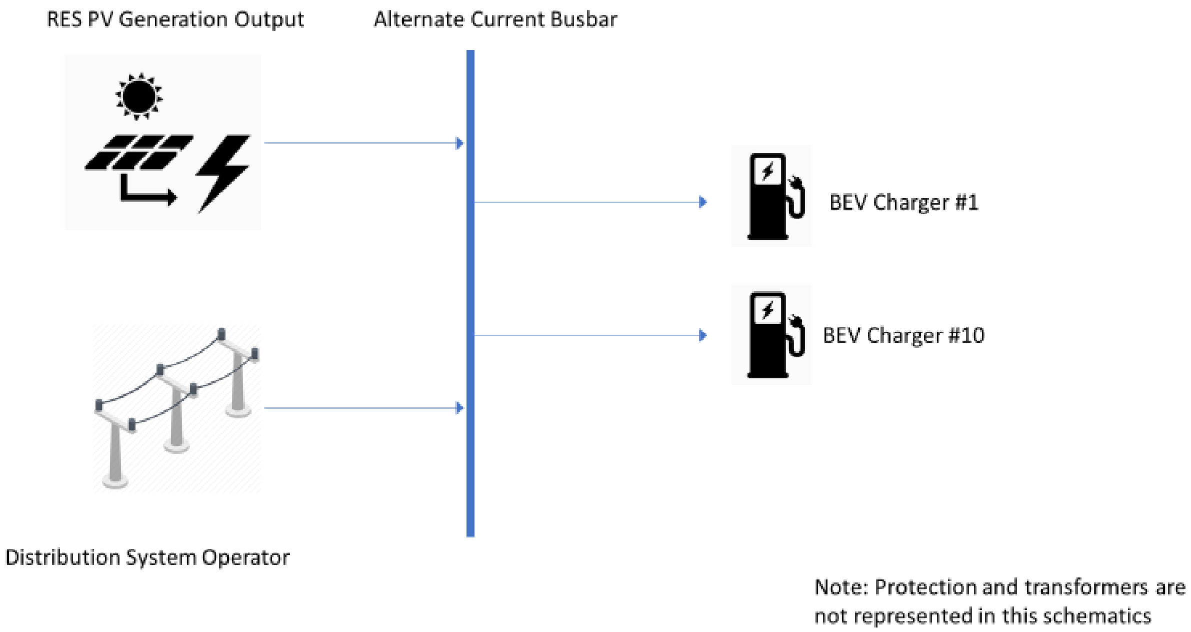

Figure 15 Renewable Energy Source Integration Scenario Schematic

The Photovoltaic generation has an intermittent energy production. This is due to the solar radiation exposition. Figure 16 has a representation of three days of three different seasons of the year (Spring and Autumn are being considered has one season) and shows the output electrical power of the panels. It was considered the panels efficiency of 17%.

For the year considered for the simulation, the peak power output was 95kW and the energy produced through the year was 163.946kWh. This represents 38% of the load energy consumption however, there is 63.995kWh of excess production.

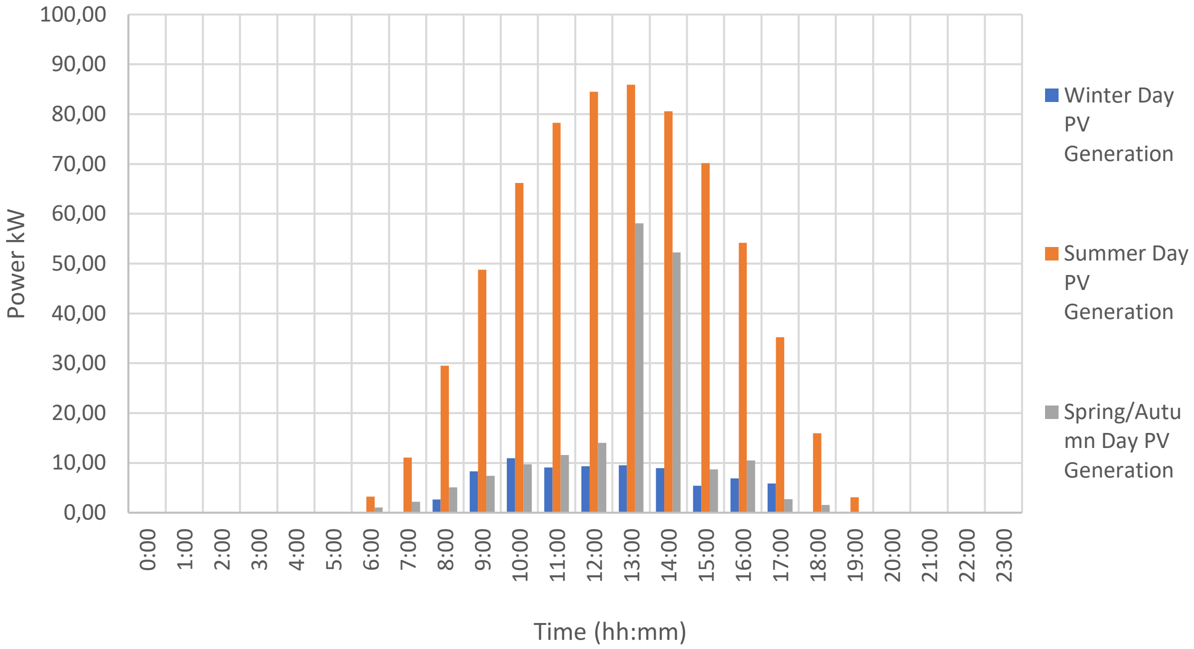

Figure 16 Three days of PV generation for the year 2015

In comparison to the baseline scenario, the load diagram is the same, but now with the PV generation in the mix, the demand power to the energy supplier is different.

The same three days were selected to see the difference between the seasons and to observe the impact that a renewable energy source has in the same BEV fast charging station.

Figure 17 graphically represents the power of the three components of this installation (Load, Electrical Grid and PV) on the selected winter day. As it can be seen the electrical grid has to cope with the majority of the electrical load because of the lower power output of the photovoltaic generation.

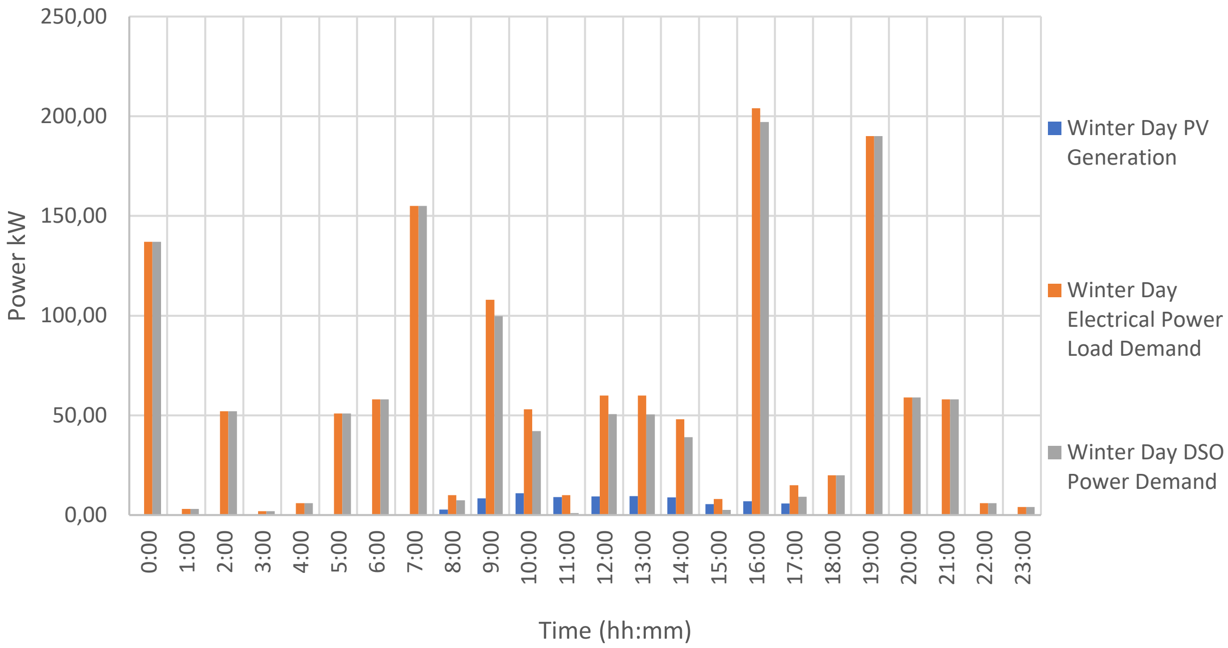

Figure 17 Winter day load diagram, power demand and PV generation

For the summer day, in Figure 18 it can be seen that the power demanded to the electrical grid, connected to the charging station, is very low. Moreover, between 10:00 until 16:00 there is no need for power from the DSO.

There is an excess of energy generation that can be sold to the distribution system operator or stored and used later. The sell of excess energy is not considered in the scope of this dissertation, therefore is not considered in the operation costs of the fast charging infrastructure.

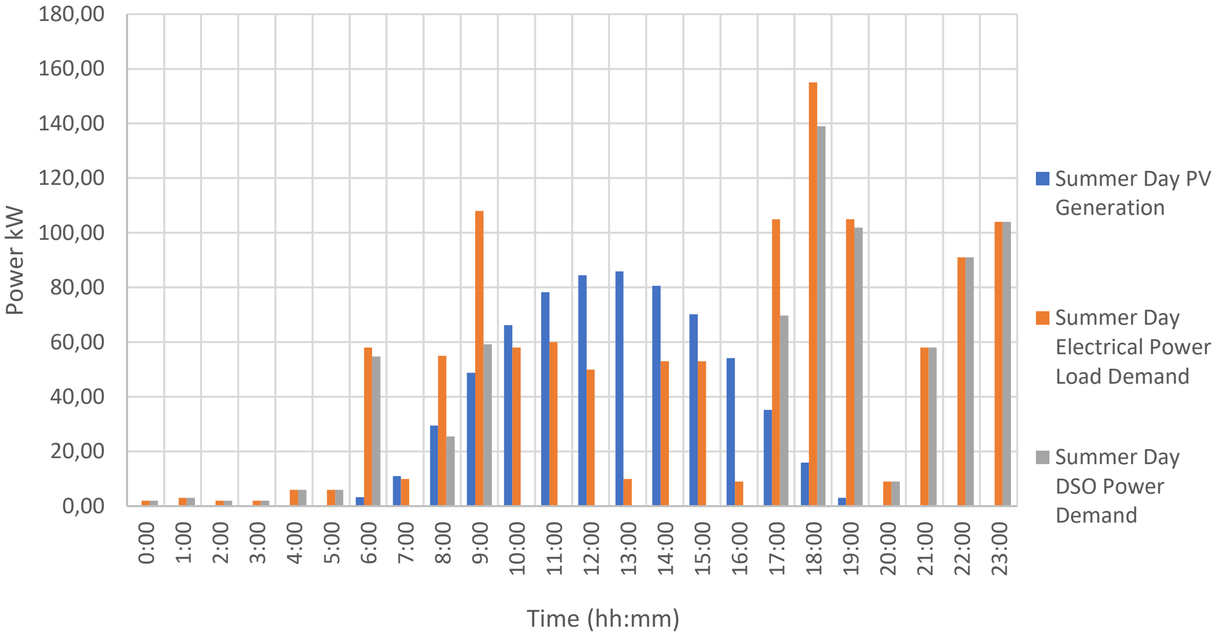

Figure 18 Summer day load diagram, power demand and PV generation

The selected day for spring/autumn is shown in Figure 19. In four hours of the day there was no need for power and energy from the electrical grid.

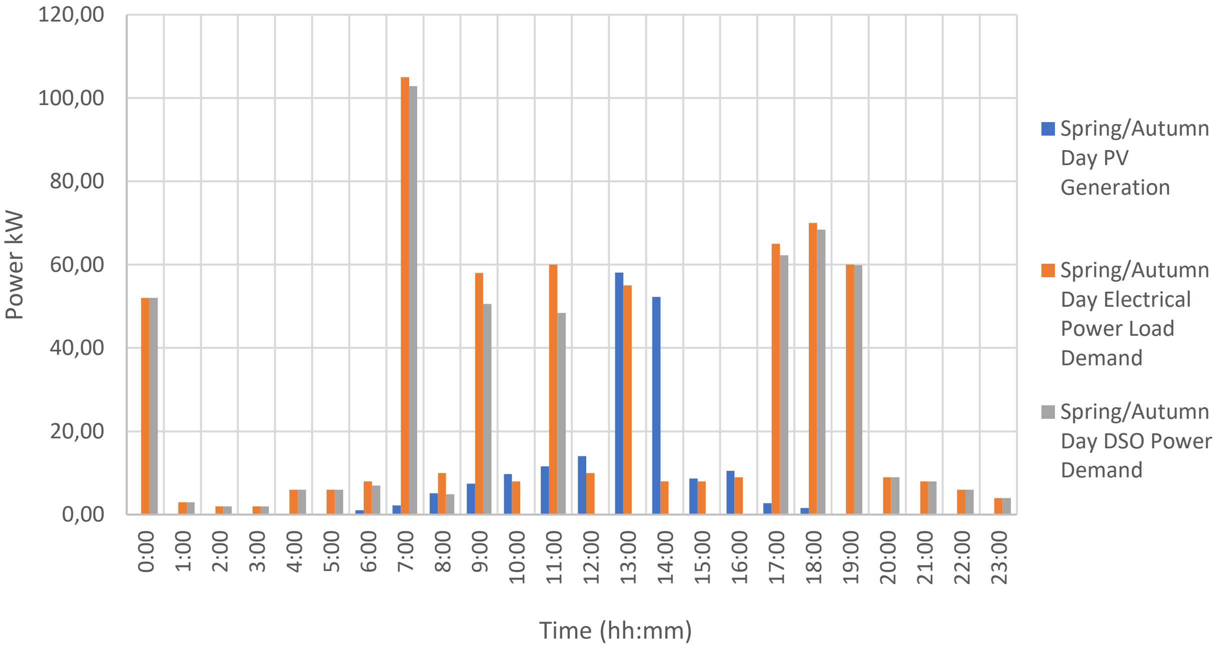

Figure 19 Spring/Autumn day load diagram, power demand and PV generation

The energy and power demanded are bought to the energy supplier is lower when compared to the baseline scenario. The maximum power contracted is lower 13kW and the energy consumption through the year is lower 31%.

### 4.1.3. BATTERY ENERGY STORAGE SYSTEM INTEGRATION SCENARIO

In the third scenario, it was added a battery storage system, without RES, to the first scenario. The same electrical load is used to compare both scenarios (baseline and this one). The sizing of the BESS is optimized according to the methodology in chapter 3. The BESS is restricted to seven discharge cycles per week in order balance battery degradation. The installation one-line diagram is shown in Figure 20.

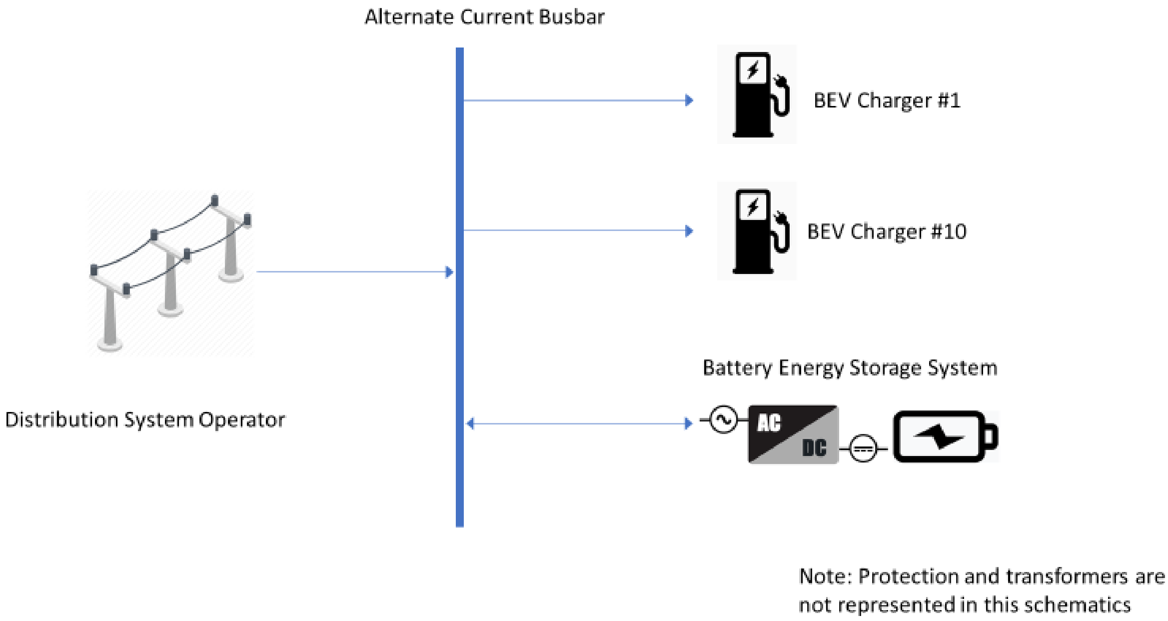

Figure 20 Battery Energy Storage System Integration Scenario Schematic

For the comparison with the other scenarios, it was selected two days. One that represents the summer and one the winter. The reason for this choice is based on the electric energy price that is divided into two periods, one representative of the winter days and the other representative of the summer days. This could translate in more pronounced energy time shift in one period instead of the other.

In order to analyse Figure 21 and Figure 22, it should be known that the positive values of power of the BESS means that the energy storage system is charging and the negative values means that the system is discharging.

The optimal sizing for the BESS, in this case study, is 438kW of power and 438kWh of energy. This means that the system has to be able to operate at a C-rate of 1C. This is due to the need of charging the BESS with higher frequency to be able to peak shave the next peak load demand. This means that the power of charging the BESS has to be high so that it can charge the amount of energy needed for the next period.

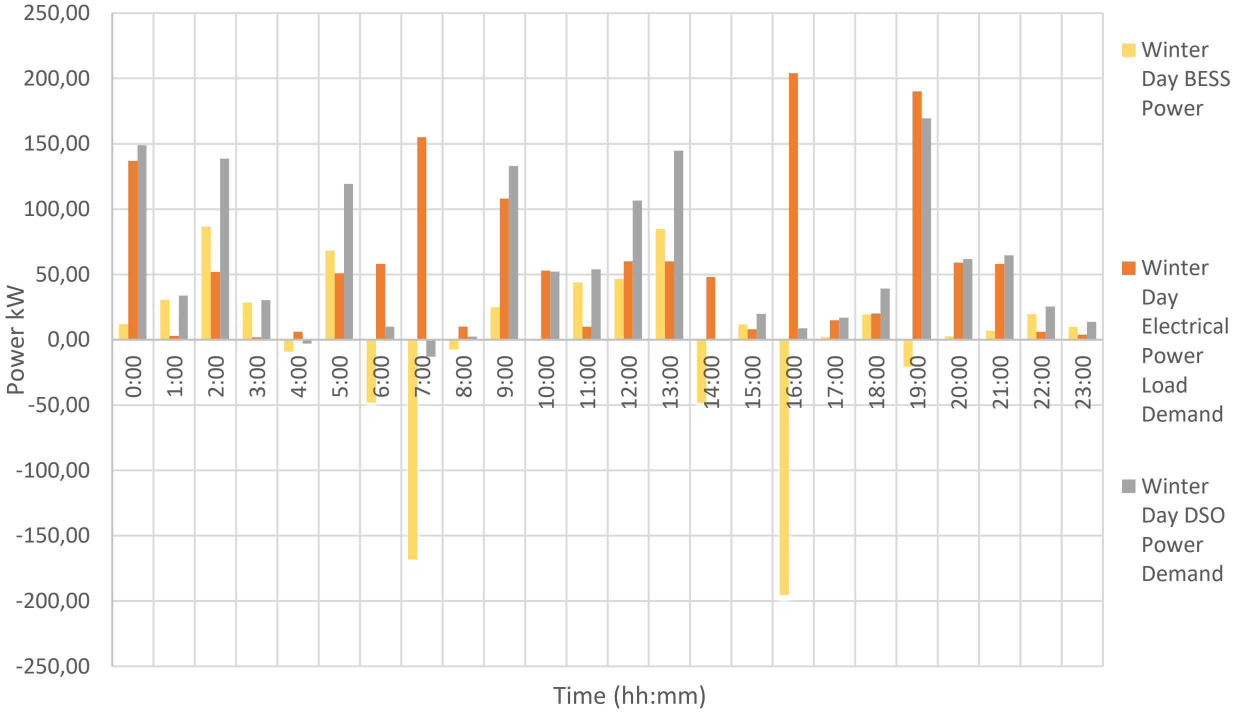

Figure 21 Winter day DSO and load power demand and BESS charge/discharge power

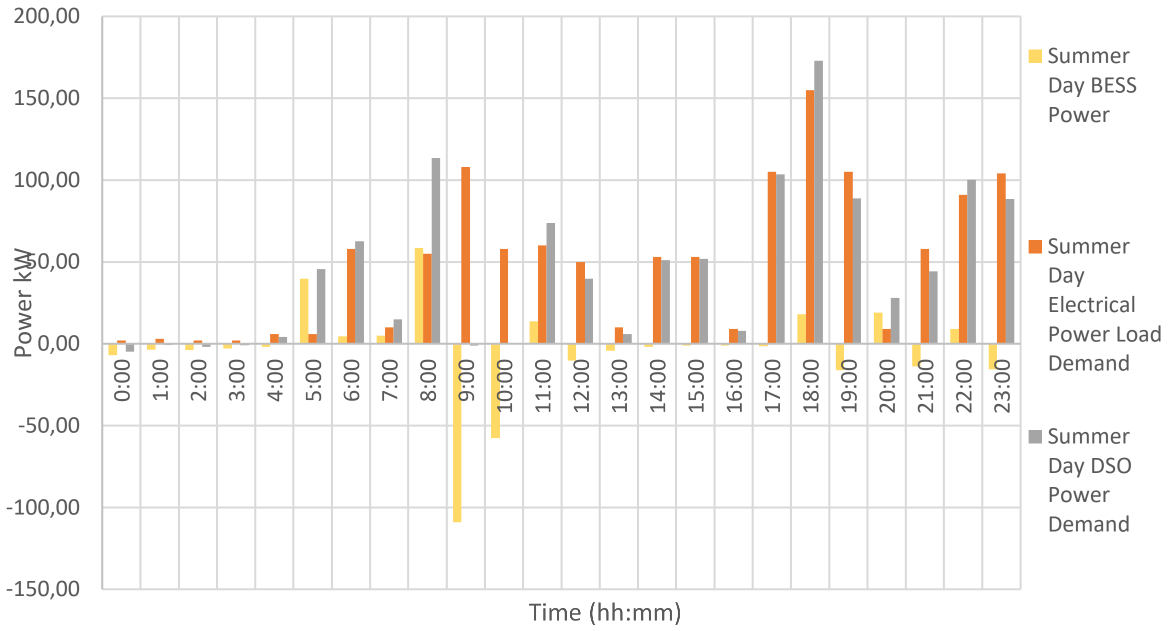

Figure 22 Summer day DSO and load power demand and BESS charge/discharge power

The Battery Energy Storage System is helpful in the periods for which the energy price is higher, and the power demand is greater. The BESS provides a peak shaving to the power demanded using off-peak energy (time shifting).

### 4.1.4. BATTERY ENERGY STORAGE SYSTEM WITH RENEWABLE ENERGY SOURCE INTEGRATION SCENARIO

The fourth scenario adds a battery storage system to a renewable energy source coupled to the distribution operator. The characteristics of the RES are the same presented in 4.1.2. The same electrical load is used to compare both scenarios (baseline and this one). The sizing of the BESS is optimized according to the methodology in chapter 3. The BESS is restricted to seven discharge cycles per week in order to balance battery degradation. The installation one-line diagram is shown in Figure 23.

The optimal sizing for the BESS, in this case study, is 250kW of power and 303kWh of energy. This means that the system has to be able to operate at a C-rate of 0,8C. This is due to the need of charging the BESS with higher frequency to be able to peak shave the next peak load demand. This means that the power of charging the BESS has to be high so that it can charge the amount of energy needed for the next period. In this case the PV output allows the power of the BESS to be lower an therefore a lower C-rate when the batteries are charging.

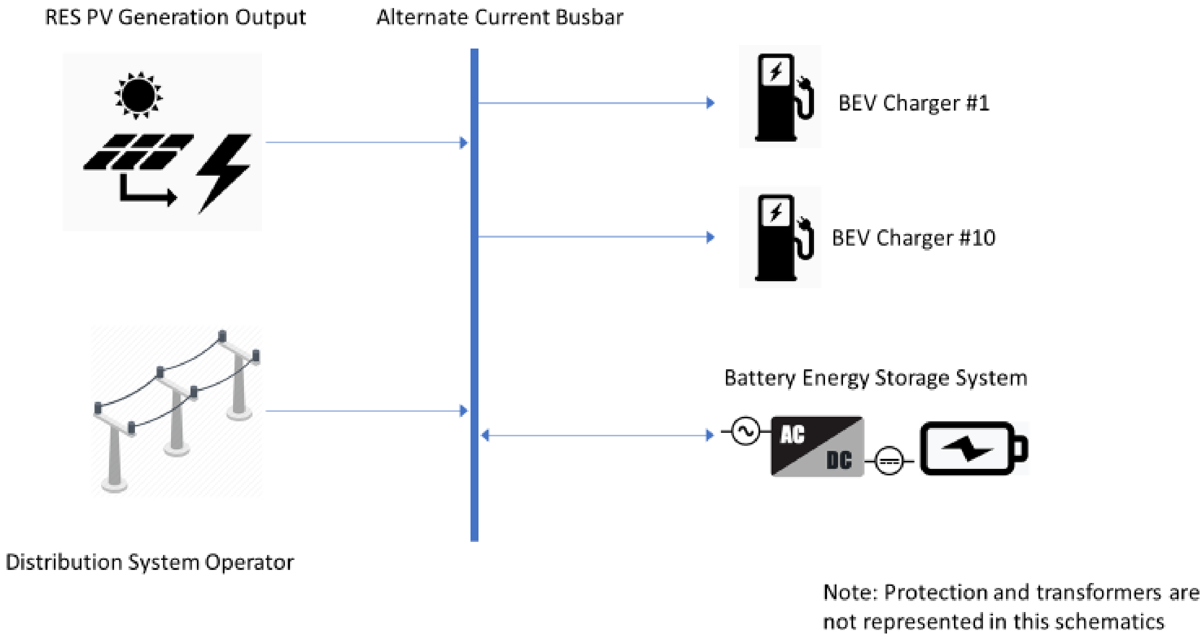

Figure 23 Battery Energy Storage System with Renewable Energy Source Integration Scenario Schematic

For the comparison with the other scenarios, it was selected three days. One that represents the summer, one the winter and the last one the spring/autumn. The reason for this choice is based on the electric energy price that is divided in two periods. This could translate in more pronounced time shift in one period instead of the other. And the photovoltaic generation which has a big impact depending on the season of the year (Figure 16).

The Battery Energy Storage System is helpful in the periods for which the energy price is higher, and the power demand is greater. The BESS provides a peak shaving to the electrical load using the energy bought through the night, when it is cheaper (time shifting).

In the summer, where the power generated by the photovoltaic panels is considerably higher, the afternoon is very different. On the day shown in Figure 25, the power generated by the PV is enough to cope with the demand and to charge the batteries. This condition demands lower power from the electrical grid and therefore lower costs with energy.

The spring/autumn (Figure 26) is very similar to the summer day but has fewer hours of solar exposition and lower radiation when the is shining. This implies a greater demand of power from the electrical grid, therefore more costs with electrical energy.

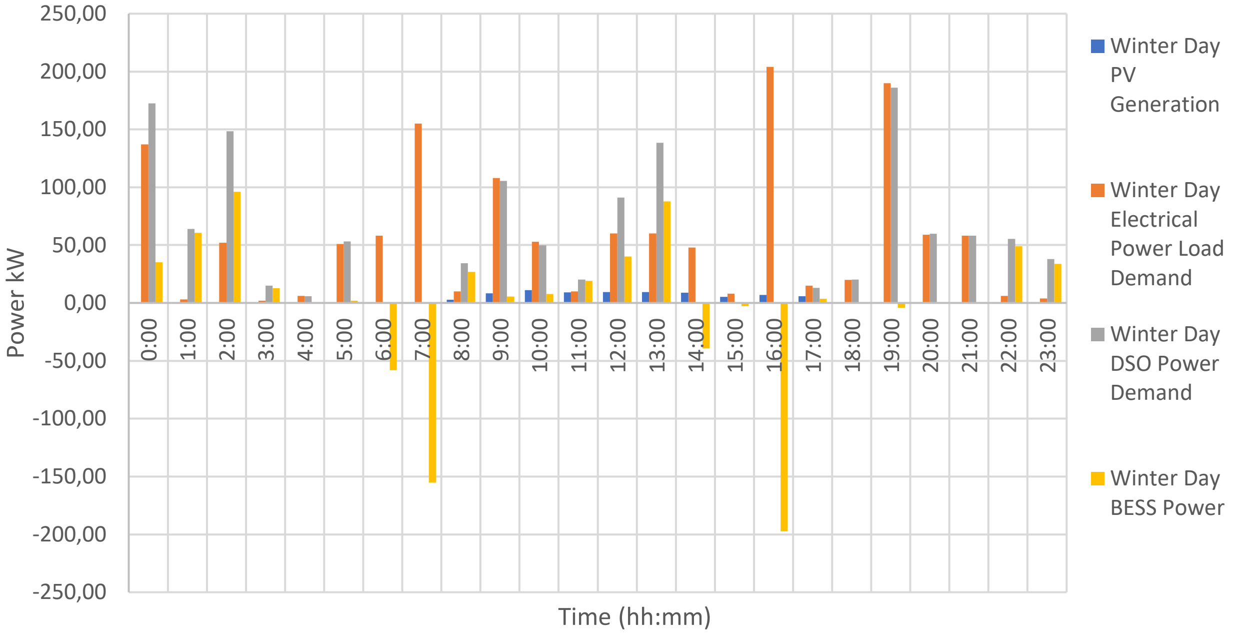

Figure 24 Winter day load diagram, power demand, PV genetation and BESS charge/discharge power

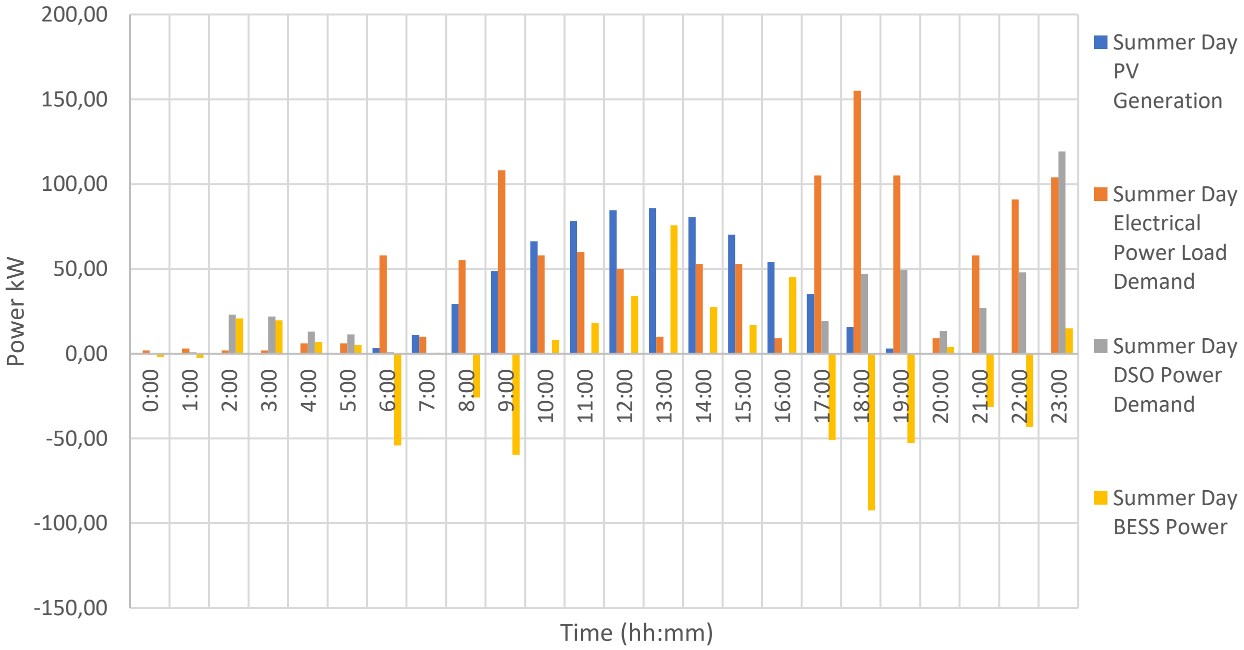

Figure 25 Summer day load diagram, power demand, PV genetation and BESS charge/discharge power

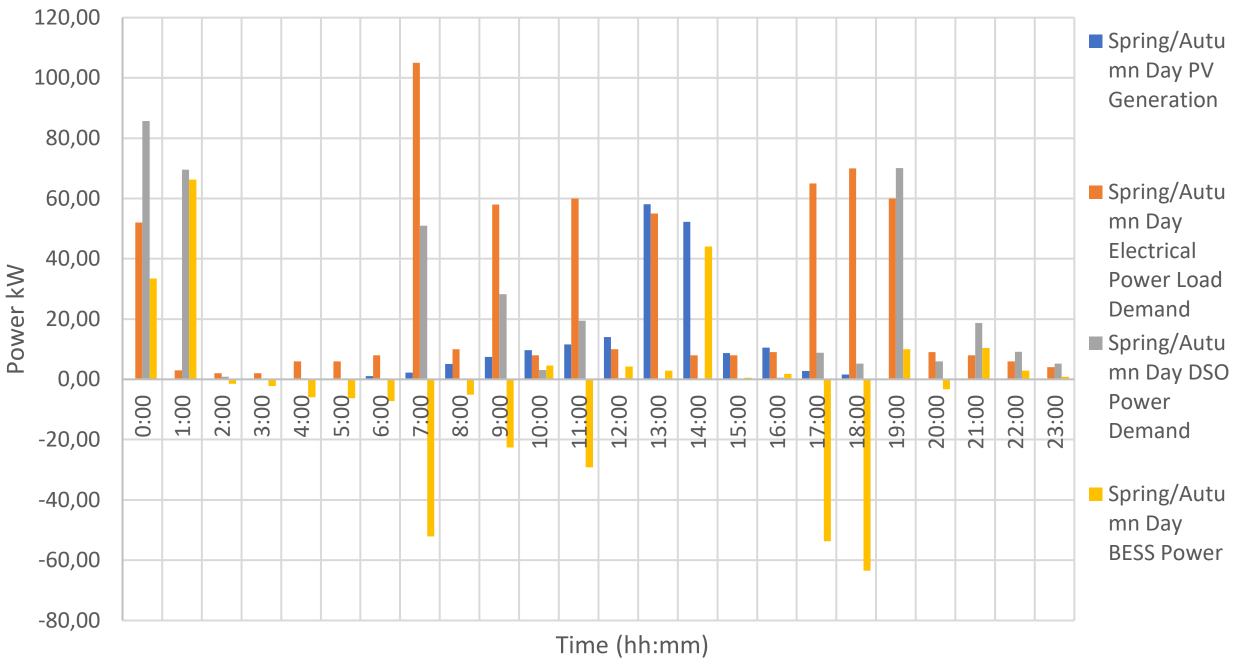

Figure 26 Spring/Autumn day load diagram, power demand, PV genetation and BESS charge/discharge power

### 4.1.5. SUMMARY COMPARISON OF THE SCENARIOS

This section gives a summary comparison between the main results, focusing on comparing the three scenarios with the baseline scenario. This is summed on Table 2, that centres on the baseline scenario and present the differences between this baseline and the others.

The negative values represent the savings, while the positive values represent the increase costs. Moreover, the table contains the sizing of the BESS for each scenario where the implementation of the energy storage system is applicable.

The BESS integration scenario presents a case that is not economically viable, taking into consideration the conditions of this study. This does not mean that this scenario can be excluded as a viable business case. For instance, if a contracted power limit is established and if that limit is surpassed, the economic evaluation is different and, in this scenario, it can become economically viable to integrate a Battery Energy Storage System.

Table 2 Scenarios comparison with the baseline scenario

| | **Cost of Operation (€)** | **Cost of Energy (€)** | **Contracted Power (kW)** | **BESS Annual Investment (€)** | **BESS Annual Maintenance (€)** |
|---|---|---|---|---|---|
| **Baseline Scenario** | 46.919,11 | 46.585,60 | 580 | - | - |
| **RES Integration Scenario (PV:95kWp)** | 40.267,46 | 35.573,04 | 567 | - | - |
| **BESS Integration Scenario (BESS:438kW/438kWh)** | 68.535,71 | 41.206,07 | 544 | 27.329,64 | 6.306,84 |
| **BESS with RES Integration Scenario (BESS:250kW/303kWhPV: 95kWp)** | 44.813,58 | 26.304,65 | 505 | 18.313,93 | 4.226,29 |

## 4.2. SENSIBILITY ANALYSIS

A sensibility analysis is needed to complete the study on Battery Energy Storage Systems in BEV fast charging stations. The number of discharge cycles and the implementation costs impact largely in the economic viability of the integration of such systems.

In Table 3, the analysis serves to perceive how the sizing changes and above all how does the number of discharge cycles impacts in the energy costs savings.

The number of cycles affects the sizing of the BESS and the costs of operation of the infrastructure. When the BESS is allowed a higher number of discharge cycles, the sizing of the BESS increases, this is due to the fact that there is a higher frequency and intensity of charging and discharging and therefore this allows the Battery Energy Storage System to use cheaper energy in more periods of high priced energy but it has to reach higher peaks of power when re-charging the batteries to be ready on time for ne next load peak demand.. The reverse logic applies to a lower limit of discharge cycles.

The BESS integration without RES it is no possible to make a comparison due to the lack of values for the scenario with three discharge cycles per week. This is due to a solution infeasibility. The optimization algorithm did not found a solution that had all the restrictions satisfied.

Table 3 Discharge cycle comparison

| | **Cost of Operation (€)** | **Cost of Energy (€)** | **Contracted Power (kW)** | **BESS Annual Investment (€)** | **BESS Annual Maintenance (€)** |
|---|---|---|---|---|---|
| **BESS Integration Scenario (BESS:438kW/438kWh 7 discharge cycles)** | 68.535,71 | 41.206,07 | 544 | 27.329,64 | 6.306,84 |
| **BESS Integration Scenario (BESS: 438kW/438kWh 14 discharge cycles)** | 68.818,73 | 41.487,79 | 579 | 27.330,94 | 6.307,14 |
| **BESS Integration Scenario (BESS: -kW/-kWh 3 discharge cycles)** | - | - | - | - | - |
| **BESS with RES Integration Scenario (BESS:250kW/303kWh PV:95kWp 7 discharge cycles)** | 44.813,58 | 26.304,65 | 505 | 18.313,93 | 4.226,29 |
| **BESS with RES Integration Scenario (BESS: 234kW/273kWh PV:95kWp 14 discharge cycles)** | 42.185,02 | 26.857,18 | 544 | 15.327,84 | 2.554,64 |
| **BESS with RES Integration Scenario (BESS: 203kW/272kWh PV:95kWp 3 discharge cycles)** | 45.489,2 | 30.478,19 | 505 | 15.011,01 | 2.501,84 |

The analysis of the implementation costs is comparable to the baseline scenario in Table 4. In this table it can be identified the future perspective of implement energy storage systems in an economically viable way.

The step-down costs of implementation are based on the forecast for the next years. Cost reduction allows the Battery Energy Storage System to enhance the size of it and therefore being capable of decreasing the costs with energy and store more surplus energy from the RES.

Table 4 Implementation Costs comparison

| | Cost of Operation (€) | Cost of Energy (€) | Contracted Power (kW) | BESS Annual Investment (€) | BESS Annual Maintenance (€) |
|---|---|---|---|---|---|
| **Baseline Scenario** | 46.919,11 | 46.585,60 | 580 | - | - |
| **BESS Integration Scenario (BESS:461kW/461kWh 60€/kW-200€/kWh)** | 55.119,45 | 40.931,09 | 546 | 14.188,36 | 3.274,24 |
| **BESS Integration Scenario (BESS:438kW/438kWh 30€/kW-100€/kWh)** | 50.131,4 | 42.729,29 | 546 | 7.402,10 | 1.708,18 |
| **BESS with RES Integration Scenario (BESS:289kW/450kWh PV:95kWp 60€/kW-200€/kWh)** | 38102,61 | 25.219,05 | 568 | 12.883,56 | 2.147,26 |
| **BESS with RES Integration Scenario (BESS:379kW/585kWh 30€/kW-100€/kWh)** | 33.053,74 | 24.669,23 | 534 | 8.384,52 | 1.397,42 |

# 5. CONCLUSION AND FUTURE WORK

## 5.1. CONCLUSIONS

This dissertation presents a tool that minimizes the operational costs of a battery electric vehicle fast charging station with an optimal sizing of a battery energy storage system. The optimization takes into consideration the costs with energy, contracted power, BESS integration and maintenance. This tool allows the operator of a fast charging station to evaluate the economic and technical benefits of integrating an energy storage system.

The methodology used for the approach of the load demand of battery electric vehicle fast charging by a probabilistic approach served the purpose for this dissertation. In the mentioned approach, we incorporate the modelling of the flow of electric vehicles that arrives at the fast charging station and the capacity and the state of charge of their batteries. Also, we used a real input radiation data to obtain the photovoltaic generation.

The integration of renewable energy sources in BEV charging infrastructures is very important for the decarbonization and all goals set from a variety of institutions and political entities. For instance, with RES integration (photovoltaic generation), the BESS will harness the excess production and will use it to peak shave the load power demand. This will result in a lower cost of operation for the fast charging station.

The analysis of the case study verifies that the costs of operation of the fast charging station with the BESS integration with renewable energy source decrease, and the contracted power is reduced. The Battery Energy Storage System enables the infrastructure to store surplus energy of the RES and time shifts the off-peak energy and uses it when the energy is more expensive. This brings savings in the operation costs and helps mitigate technical grid constraints (triggered by the BEV charging). For proving that a BESS is a very beneficial choice for BEV fast charging stations.

In the case study of this dissertation, we concluded that the BESS explores the difference between the hourly rates, and the sizing of the system is impacted by it. If the difference between the hourly rates reduce, the benefits of the BESS diminish. On the other hand, if the difference increase, the benefits of the Battery Energy Storage System enhance.

The Battery Energy Storage System addresses technical and economic challenges for the operator of the BEV fast charging infrastructure microgrid. From the distribution system operator point of view, the BESS can provide ancillary services to cope with challenges such as voltage deviation, harmonic distortion, increase in power and energy demand at peak hours and the overloading of the distribution network equipment such as transformers, feeders, switchgear, etc.

The DSO has benefits when the capability for time shifting is added to the electrical infrastructure and when a high amount of load demand is being considered it brings even more benefits. This could lead to an energy price review when energy storage systems are being deployed in an infrastructure that charges battery electric vehicles, that are non-linear and high power consumption, in a short amount of time, electrical loads. An increase of price at peak hours with heavy penalties and a decrease of energy cost at off-peak hours will help the economic viability to BESS implementation, solving problems for both players.

A parallelism to the energy price reduction at peak hours is seen when the implementation costs are reduced. This can be seen in the costs sensibility analysis where the sizing of the BESS becomes bigger and energy cost savings and operational costs became lower.

The integration of the BESS results in benefits for both operators and this means that in the future the DSO could change energy costs in order to benefit the integration of energy storage systems.

## 5.2. FUTURE WORK

The future work, in order to improve this optimization tool, technical restrictions that simulate grid restrictions must be added. These restrictions must be paired with additional decision variables and associated costs. These costs could be lost opportunities for charging BEVs when contracted power limits are reached.

In the future improvement of this work, the decrease capacity of the batteries through their life should be considered and the costs associated should be reflected. This pairs with the costs with lost opportunities, where the degradation of the battery can lead to the unavailability to charge all the EVs connected to the charging station. A way to solve this is to size the BESS to an end of life operation where the energy storage system sizing must be able, in its end of life, to address the load demand. This will lead to an oversizing of the battery at beginning of life and it will increase the costs with implementation and also the costs of operation.

Moreover, the benefits for selling energy should be taken in consideration in future work. This could be considered in RES excess energy produced, the amount that was not been able to store. If there is a lower demand for charging and the BESS could sell energy where the price is favourable. An example of this could be in situations like a pandemic scenario where there are close to no vehicles charging however there is still a chance to soothe the operation costs.

Smart charging scenarios should be considered. In this case, we should have a more controllable load and sizing of the BESS will be very different. Also, scenarios with more power sources such cogeneration can be a reality to fast charging in industrial condominiums. Not only that but the vehicle to grid function should be a clear next step to the optimal sizing tool. More technical approaches can be added and a step to a technical-economic approach achieved. These approaches should be integrating a scenario where the off-grid operation should be taken into consideration. Also, a comparison with all these scenarios between an AC and a DC grid, and all the added costs that must be considered.

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# APPENDIXES

# Appendix A. Description

Table 5 United States vehicle trip distribution on weekdays and weekends

| **Time of day (h)** | **Weekday probability of daily trips** | **Weekend probability of daily trips** |
|---|---|---|
| 0 | 0,009 | 0,017 |
| 1 | 0,007 | 0,014 |
| 2 | 0,005 | 0,012 |
| 3 | 0,006 | 0,01 |
| 4 | 0,009 | 0,009 |
| 5 | 0,015 | 0,01 |
| 6 | 0,027 | 0,012 |
| 7 | 0,049 | 0,017 |
| 8 | 0,071 | 0,028 |
| 9 | 0,067 | 0,04 |
| 10 | 0,05 | 0,05 |
| 11 | 0,052 | 0,06 |
| 12 | 0,053 | 0,066 |
| 13 | 0,054 | 0,067 |
| 14 | 0,055 | 0,068 |
| 15 | 0,06 | 0,069 |
| 16 | 0,072 | 0,068 |
| 17 | 0,083 | 0,067 |
| 18 | 0,085 | 0,062 |
| 19 | 0,06 | 0,058 |
| 20 | 0,047 | 0,053 |
| 21 | 0,036 | 0,047 |

| | | |
|---|---|---|
| 22 | 0,031 | 0,036 |
| 23 | 0,028 | 0,031 |
| 24 | 0,020 | 0,025 |